Static Control for Roll-to-Roll Manufacturing

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***Abstract*—Roll-to-Roll (R2R) manufacturing is used extensively in printing and flexible packaging industries. These commercially important markets exceeded $30B USD annually in the US in 2019 with employment of about 79,000. In addition, R2R operations are increasingly used to produce flexible electronic products and medical devices, which are easily damaged by electrostatic discharges (ESD). Many materials used in R2R operations such as polypropylene are insulating making them prone to accumulating static charges. Sparks from accumulated charges can ignite fires, injury employees, and damage products. Accumulated charges also cause static cling, which can disrupt machine operations. I estimate that waste caused by static electricity from injuries, damaged products, and machine downtime exceeds $600M USD annually in the US. This human suffering and waste may be eliminated by effective static control systems. Implementing effective static control on an R2R manufacturing line is a 4-step, data-driven process. First, identify sources of static charging with a static survey. Next, install static dissipaters forming a fault-tolerant, static control system. Once static dissipaters are operational, verify that static is well controlled with second static survey. Lastly, maintain static performance by regularly verifying static performance and by including static control in Management of Change procedures.**

***Index Terms*—Electrostatic analysis, electrostatic processes, ESD, hazardous areas, manufacturing processes, plastics industry, safety, sparks.**

I. Introduction

IN ROLL-to-Roll (R2R) manufacturing, products are produced on continuous, flexible, webs of paper, plastic, and metal foils. Webs may be formed by extruding a hot, molten polymer such as polypropylene (PP) onto a chilled roller. The cooled polymer is stripped from the chilled roller forming a continuous, flexible web. At the end of extrusion or casting lines, webs are wound into rolls to be delivered to subsequent manufacturing operations including printing, coating, lamination (forming a single web from two incoming webs), and slitting (cutting the web lengthwise into multiple, narrower webs). Products produced by R2R manufacturing include flexible packaging (e.g., bags, tubes), packaging films, and labels. While I use the terms web and film interchangeable, web is the more general term. Film refers to a web with a specific formulation or coating.

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In R2R manufacturing operations, static electricity presents risks to employees, product quality, and production operations. When insulating webs such as polypropylene (PP) or polyethylene terephthalate (PET) are conveyed through solvent coaters or printing operations using ignitable inks, static sparks from these webs can ignite solvent vapors. Static charges stored on winding rolls can shock operators. The sparks from wound rolls, some longer than two feet, cause shocks to personnel that require hospitalization or worse. Lower energy shocks can cause secondary injuries such as falls. Static sparks can damage thin coatings such silicone release layers or other sensitive coatings having chemical or electronic functionalities. Static charges on films attracted airborne contaminates particularly during slitting and punching operations.

Injuries and economic losses from static in R2R operations motivate improvements in static control. R2R manufacturing is big business with revenues exceeding $30B annually in the US in 2019 [2] with employment of about 79000. I estimate that static causes injuries, damaged products, and machine downtime waste on the order of 2% totaling more than $600M USD annually in the US.

R2R operations are increasingly used to produce flexible electronic products and medical devices. Such devices are easily damaged by the energetic electrostatic discharges that can occur in R2R operations where static is not well controlled. Excellent static control will be needed for the manufacture of electronic and medical devices in R2R lines.

Efforts to improve the static control in R2R operations date back to at least 1904 when William Chapman patented a method of removing static electricity from paper and yarn [3]. The following comments are from US Patent 777598. "Static electricity generated by friction and by the separation of surfaces is often the source of great annoyance and delay in the operations of various kinds of machinery – as, for instance, in the calenders of paper-machines, in printing-presses, and in the machinery for working different kinds of fabrics – and it becomes of great importance to neutralize these static charges in order that the machinery may be worked in an efficient manner and at a desirable rate of speed. In the handling of paper, the sheets of paper stick to each other and to other surfaces, causing breakage and delay, and to prevent these difficulties, a variety of devices have been tried in the past with unsatisfactory results."

These comments from 1904 apply equally well to our present day R2R operations.

II. Overview of Static Control

Implement an effective static control system by following the 4-step process in Table I.

TABLE I
4-STEP DATA-DRIVEN PROCESS

A.	Identify static charging sources.
B.	Install static dissipaters.
C.	Verify static performance.
D.	Maintain static performance.

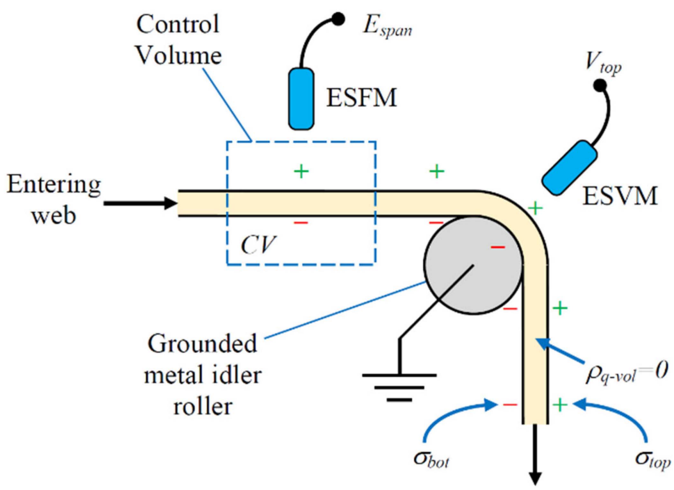

Fig. 1. Charge densities σ_{top} and σ_{bot} are measured by E_{span} and V_{top}.

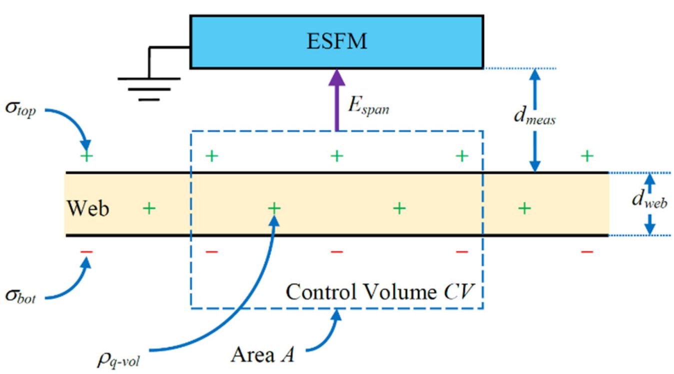

Fig. 2. Charges may be on the top, bottom, or inside the web.

A. *Identify Static Charging Sources*

Identifying sources of static charging is key to effective control as discussed in III. STATIC CONTROL SYSTEM DESIGN. These sources of static charging may be identified by completing a static survey, which is a series of electrostatic measurements along the material flow from incoming materials to finished products. Two commercially available instruments are used to measure static; an electrostatic fieldmeter (ESFM) and an electrostatic voltmeter (ESVM).

The ESFM in Fig. 1 responds to the net charge density σ_{net} on the web as seen by applying Gauss's Law (1) to control volume *CV* in Fig. 2.

$$\oint_{CV} \varepsilon_0 \vec{E}_{span} \cdot \vec{ds} = \iiint_{CV} \rho_{vol} dv \tag{1}$$

The permittivity of free space ϵ_0 in (1) is a physical constant. The electric field E_{span} from the charges on the web in Fig. 2 terminate on the ESFM represented by a grounded plate. Assuming that the charge densities are uniform, E_{span} is uniform and Gauss's law in (1) evaluates to (2).

$$\varepsilon_0 E_{span} A = \sigma_{top} A + \sigma_{bot} A + \rho_{vol} d_{web} A \tag{2}$$

Solving (2) for E_{span} results in (3).

$$E_{span} = \frac{\sigma_{top} + \sigma_{bot} + \rho_{vol} d_{web}}{\varepsilon_0} = \frac{\sigma_{net}}{\varepsilon_0} \tag{3}$$

The net charge density σ_{net} in (3) is the sum of all charges on the web in Fig. 2; charge density σ_{top} on the top surface, charge density σ_{bot} on the bottom surface, and volumetric charge density ρ_{vol} distributed through the volume of the web.

Normally, static charges are on the web surfaces and the volumetric charge density ρ_{vol} is zero. Some operations can cause charges to be in the volume of the web. For example, the one or both of the two webs entering a laminator may have static charges on the surface to be laminated resulting in charges on the interface inside the exiting, laminated web.

One simplifying assumption in Fig. 2 is that the ESFM is a large, grounded plate. While an ESFM is not large, grounded plates as modelled in Fig. 2, it is calibrated by the manufacturer to display the electric field that would be present if it was a large, grounded plate [4].

For example, when E_{span} is 2 kV/cm (5 kV/inch), the net charge density σ_{net} is found in (4) to be 1.7 μC/m^2. This charge density is a common criterion for low static [5].

$$\sigma_{net} = \varepsilon_0 E_{span}$$
$$= \left(8.854 \times 10^{-12} \frac{F}{m}\right) \left(5.0 \frac{kV}{in}\right) \left(\frac{1}{0.0254} \frac{in}{m}\right) \left(10^{+3} \frac{V}{kV}\right)$$
$$= 1.7 \times 10^{-6} \frac{C}{m^2} = 1.7 \frac{\mu C}{m^2} \tag{4}$$

A change in the ESFM reading in Fig. 1 from one location to the next indicates a change in the amount of net charge on the web. This change in net charge is caused by a source of static charging between these two locations that deposited static on the web.

The ESVM in Fig. 1 responds to the surface charge density σ_{top} on the exposed surface of the web wrapped on the grounded, metal idler roller. Since the web thickness d_{web} is small compared with the idler roller radius, the ESVM response is modelled in (5) by a parallel plate capacitor.

$$\sigma_{top} = \frac{\varepsilon_0 \kappa_{web}}{d_{web}} V_{top} \tag{5}$$

Solving (5) for V_{top} results in (6).

$$V_{top} = \frac{d_{web}}{\varepsilon_0 \kappa_{web}} \sigma_{top} \tag{6}$$

The surface potential V_{top} of the top surface of the web is proportional to the surface charge density σ_{top}. And, for a constant surface charge density, voltage V_{top} increases linearly with the web thickness. Use the web thickness d_{web} and the

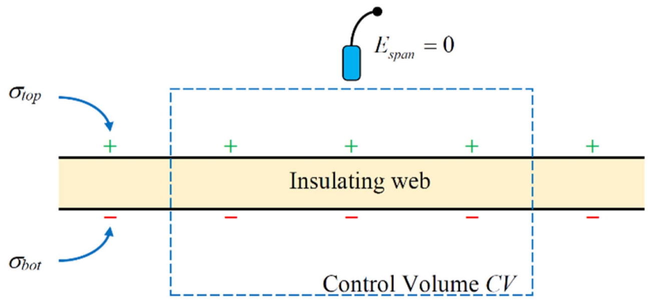

Fig. 3. E_{span}=0 because σ_{bot} is equal and opposite to σ_{top}.

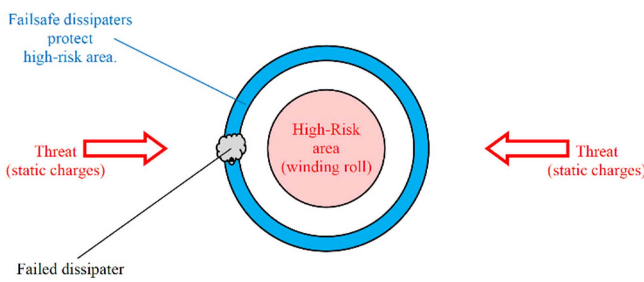

Fig. 4. Failsafe dissipaters protect the high-risk area from static charges.

material dielectric constant κ_{web} in (5) to find surface charge density σ_{top} from an ESVM measurement.

The charge densities on both sides of the web in Fig. 1 may be determined by measuring E_{span} and V_{top} using (3) and (5) with the simplifying assumption that all of the static charges are on the web surface so that ρ_{vol} in (3) is zero [6].

One very common charge distribution in R2R operations is balanced charge illustrated in Fig. 3. With balanced charges, the electric field E_{span} is zero because the net charge σ_{net} in control volume *CV* is zero.

Detect balanced charge with an ESVM. For example, with a 25 μm thick PET web ($\kappa_{web} = 3.0$) in Fig. 1, when V_{top} is 10 V, the charge density σ_{top} is found in (7) to be 10 μC/m^2. My experience is that balanced charge densities less than 10 μC/m^2 are low.

$$\sigma_{top} = \frac{\varepsilon_0 \kappa_{web}}{d_{web}} V_{top} = \frac{\left(8.85 \times 10^{-12} \frac{F}{m}\right)(3.0)}{25 \times 10^{-6} m}(10V) \cong 10 \times 10^{-6} \frac{C}{m^2} = 10 \frac{\mu C}{m^2} \quad (7)$$

B. Install Static Dissipaters

Static dissipaters are commonly used to control static in R2R operations. The high-risk area in Fig. 4 is where static causes a problem such as a winding roll where a large amount of stored charge could cause a spark that could shock an operator or a solvent handling area where a spark could ignite a fire.

Install a failsafe static dissipater in Fig. 4 to protect the high-risk area such as a winding roll or a solvent zone from incoming static. While this approach is effective, it is prone to failure. The failure of a failsafe static dissipater allows static charges to penetrate into the high-risk area.

C. Verify Static Performance

Once static dissipaters are installed and operational, perform a static survey using both an electrostatic fieldmeter (ESFM) and an electrostatic voltmeter (ESVM). The ESFM in Fig. 1 responds to the net charge density σ_{net} in (3). The ESVM in Fig. 1 responds only to the charge density σ_{top} on the exposed, top surface. Using an ESFM and an ESVM, the charge density σ_{top} and σ_{bot} can both be measured to ensure that the charge densities on both web surfaces are properly controlled.

D. Maintain Static Performance

Static problems occur in the fault-tolerant control system only when two system elements fail simultaneously. Process monitoring and system maintenance prevent static failures by detecting a failure and restoring operation of the failed component before two failures occur. Measure static levels periodically at key locations to verify performance. On-line sensors provide continuous monitoring. Including static in Management-of-Change (MoC) procedures helps identify needed changes in static control system when new charging sources are introduced by machine upgrades or process changes.

III. Static Control System Design

Fault-tolerant static control maintains satisfactory control even when any single dissipater fails. Fault-tolerant control is achieved by neutralizing static both entering high-risk areas and at sources of static charging [7]. With effective source control, the webs entering high-risk areas are nearly charge-free. Failsafe static dissipaters protecting the high-risk areas provide a redundant, second layer of fail-safe protection. Use the fewest number of dissipaters to achieve the required performance to minimize the operational burden since each dissipater requires maintenance and verification.

A. Protect High Risk Areas

Install failsafe static dissipaters as in Fig. 4 to neutralize static on web entering high-risk zones. These failsafe dissipaters are the first layer of protection. Having one layer of protection is effective. However, one layer protection is prone to failure. Failure of a single static dissipater allows the static charges to enter the high-risk area. Traditional static control using only failsafe dissipaters has been practiced since at least 1904.

B. Dissipate Static At Charging Sources

Fault-tolerant static control is achieved by installing source-control static dissipaters in Fig. 5 to neutralize static on webs exiting sources of static charging [7]. With source-control dissipaters, webs are nearly charge-free when they enter high-risk areas. So, the redundant failsafe static dissipaters protect the high-risk areas in the event that a source-control dissipater fails. Fault-tolerant static control is achieved.

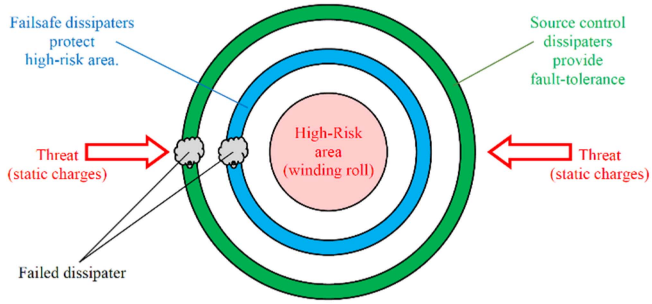

Fig. 5. The threat (static charges) penetrates to the high-risk area (winding roll) only when two system components fail.

C. Identify Charging Sources

A "static survey" is a series of electrostatic fieldmeter (ESFM) and electrostatic voltmeter (ESVM) measurements at locations along the material flow. A static survey for the typical coater in Fig. 6 has sixteen ESFM and two ESVM measurements. This example coater illustrates common, web conveyance components. The motor on the unwinding roll is controlled by a dancer roller. A web guide upstream of the coater aligns the web. The coated web surface is treated by a corona treater just before coating. After coating, the web passes through a long dryer and a web guide near the dryer exit. A chill roller cools the web. After inspection, the web passes through a nip that controls winding tension. The rewind motor is controlled by a dancer roller. Finally, the rewinding roll has a contacting roller to improve winding roll integrity.

Each of these web conveyance components, typical of a commercial coater, contribute to the static performance of the line. ESFM readings from the sixteen locations indicated in Fig. 6 are plotted in Fig. 7. The static performance of the coater is summarized by this stop-light chart showing the minimum, maximum, and average ESFM readings. The green, low static zone shows the common criterion for low static [5].

My experience is that static sparks commonly occur in the red, high static zone where electric fields exceed ± 6 kV/cm (± 15 kV/inch).

The first ESFM reading Unwind roll-1 in Fig. 7 shows that the unwinding roll has high static, which is common. The best practice is to use powered static bar SB_{unwind} to neutralize static on the outside surface of the unwinding roll [8]. Additional static control best practices are discussed in the next section.

Changes in ESFM readings from one location to the next in the stoplight chart in Fig. 7 indicate that a static charging source between the two locations has deposited charge on the web. For example, the second ESFM reading Unwind out-2 in Fig. 7 shows that the measured electric field decreased significantly compared with the previous reading. The sources of charging are two powered static bars, SB_{unwind} and SB_{span}, which deposited oppositely charged, neutralizing static on the web to neutralize the high, negative static measured on the unwinding roll.

The next, significant change is the fifth ESFM measurement CT out-5 in Fig. 7 showing that the corona treater deposited a large amount of positive charge on the web. The next ESFM reading, Coat in-6, is nearly zero showing that powered static bar SB_{CT} deposited a large amount of negative static that neutralized the positive static from the corona treater.

In the center of the stoplight chart in Fig. 7, four readings from Dry out-8 to Chill out-11 illustrate large variations in reading ranging from Guide out-9 (–7.5 kV/cm) to Chill in-10 (+5 kV/cm). These large variations illustrate uncontrolled sources of static charging. Static control may be improved in this section of the coater by installing static dissipaters in best practice locations as described in IV. Locations for Static Dissipaters and Measurements.

The charge densities on both web surfaces exiting the unwinding roll in Fig. 6 are measured as in Fig. 1 by ESVM reading V_{unwind} and ESFM reading Unwind out-2. To complete the static survey, the charge densities on both web surfaces entering the rewind roll are measured by ESVM reading $V_{rewind-2}$ and ESFM reading Rewind in-15. Comparing the final charge densities entering the rewind roll with the charge densities exiting the unwind roll is an excellent measure the overall charge control. A change in the charge densities less than ± 10 μC/m^2 indicates good charge control.

IV. Locations for Static Dissipaters and Measurements

Install static dissipaters in best-practice locations to achieve good static control. Verify performance by ESFM and ESVM measurements at best-practice locations.

A. Unwinding Roll

Neutralizing static on both surfaces of the web exiting an unwinding roll [8] protects this operation from static on the unwinding roll, which has at least two sources; tribocharging and static stored on the roll from previous manufacturing operations.

1) Tribocharging: Static charges separate whenever two chemically different materials touch and separate. When the inside surface of the web in Fig. 8 is different from the outside surface, tribocharging occurs at the unwinding nip. The web surfaces are chemically different when the web is coated or printed. Also, charges separate at the unwinding nip when the web is a laminate with different polymers on the outside and inside surfaces.

The outside surface of the unwinding roll in Fig. 8, has negative charges, while the inside surface of the exiting web has positive charges. Of course, the polarity of the charges depends on the relative positions of materials on the triboelectric series.

In steady state, the negative charges on the outside surface of the roll in Fig. 9 move with the web and exit on the outside surface of the web. For every negative charge on the outside surface, there is a positive charge on the inside surface. These charges are separated by the circumference of the unwinding roll. However, if the web has uniform composition, charges separated by tribocharging are constant in time and the web exits with positive charge on one surface and an equal amount of negative charge on the other surface. Tribocharging at the unwinding nip is a common source of balanced charge illustrated in Fig. 3.

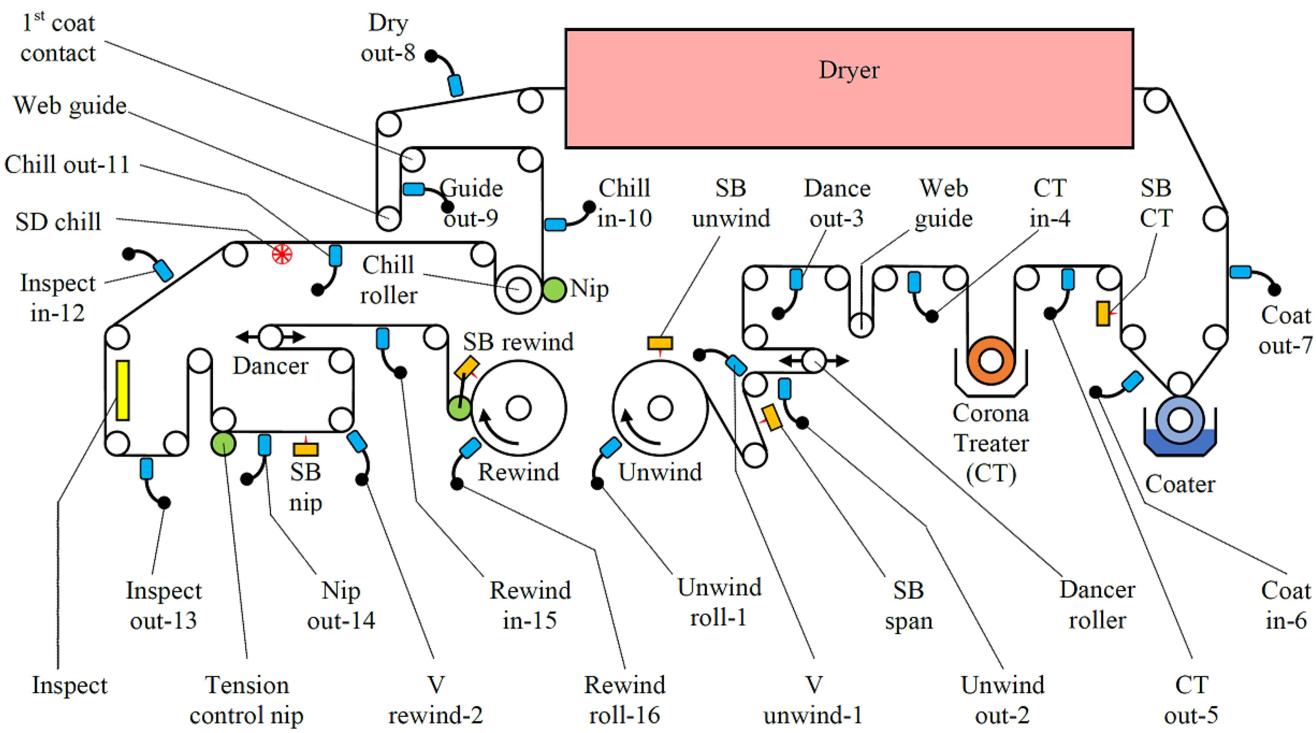

Fig. 6. The static survey of this coater has 16 electrostatic fieldmeter and 2 electrostatic voltmeter measurements.

At first inspection, the electrostatic fieldmeter measurements in Fig. 9 are confusing. E_{roll} responds to the charges in control volume CV_{roll} including charges on the outside surface of the unwinding roll. E_{roll} in Fig. 9 is large and negative showing a large amount of negative charge on the unwinding roll. Static on an unwinding roll may be sufficiently high to pose a serious shock hazard those nearby.

E_{span} in Fig. 9 responds to the net charge in control volume CV_{span}, which is zero. This is the characteristic of tribocharging at the unwinding nip. The unwinding roll has high charge while the exiting web has low net charge and large, balanced charges.

2) Process Charge: A second source of charge on an unwinding roll is process charge deposited on the web when it was wound in the previous manufacturing operation. Wound rolls can store a very large amount of charge. Even with good static control, the web entering a winding roll may carry a small amount of static. All of this static is stored on the wound roll.

The web length L_{web} having thickness d_{web} wound onto a roll have outside diameter D_{out} and core diameter D_{core} is found in (8) using conservation of volume.

$$L_{web} = \frac{\pi}{4} \frac{\left(D_{roll}^2 - D_{core}^2\right)}{d_{web}} \quad (8)$$

For example, a 1-meter diameter roll of a 50 μm thick web on a 6-inch diameter core stores a web with a length exceeding 15 km.

When the web is electrically insulating such as polypropylene, electrical charges on the web when the roll was wound persist for week, months and maybe years. These stored charges are present when the roll is unwound in the next operation.

3) Best-practice Static Dissipater Locations: Static charges on both sides of the web exiting the unwinding roll in Fig. 10 may be neutralized using two, powered static dissipaters [8]. Powered static dissipaters are often called static bars (SBs). As the roll expires, the distance from the roll surface to $\mathrm{SB_{roll}}$ in Fig. 10 increases, which reduces the neutralizing performance of $\mathrm{SB_{roll}}$. To mitigate this decrease in performance, $\mathrm{SB_{roll}}$ must be a long-range, pulsed DC static bar that is designed to have good neutralizing efficiencies at distances exceeding 0.5 meter [9].

$\mathrm{SB_{roll}}$ in Fig. 10 responds to the charges in control volume $CV_{roll\text{-}SB}$. $\mathrm{SB_{roll}}$ neutralizes the negative charges on the outside surface of the unwinding roll. $E_{unwind\text{-}roll}$, which responds to the charges in control volume CV_{roll} verifies the performance of $\mathrm{SB_{roll}}$. With $\mathrm{SB_{roll}}$, the web exiting the unwinding roll carries net charge rather than balanced charge as in Fig. 9. This is confirmed by $E_{unwind\text{-}span}$, which responds to the charges in control volume CV_{span}. $\mathrm{SB_{span}}$ in Fig. 10 responds to the charges in control volume $CV_{span\text{-}SB}$ and neutralizes the static on the inside surface of the web. Ideally, the exiting web in Fig. 10 is charge-free.

Performance of $\mathrm{SB_{roll}}$ and $\mathrm{SB_{span}}$ in Fig. 10 is verified by $V_{unwind\text{-}in}$ and E_{unwind}. E_{unwind} verifies that the web exiting the unwinding roll has low net charge. $V_{unwind\text{-}in}$ verifies that static dissipater $\mathrm{SB_{span}}$ neutralizes static on the inside surface of the web.

One authoritative reference [10] recommends neutralizing static charges on both sides of a web as in Fig. 11 where $\mathrm{SB_{bot}}$ faces the bottom web surface and $\mathrm{SB_{top}}$ faces the top surface.

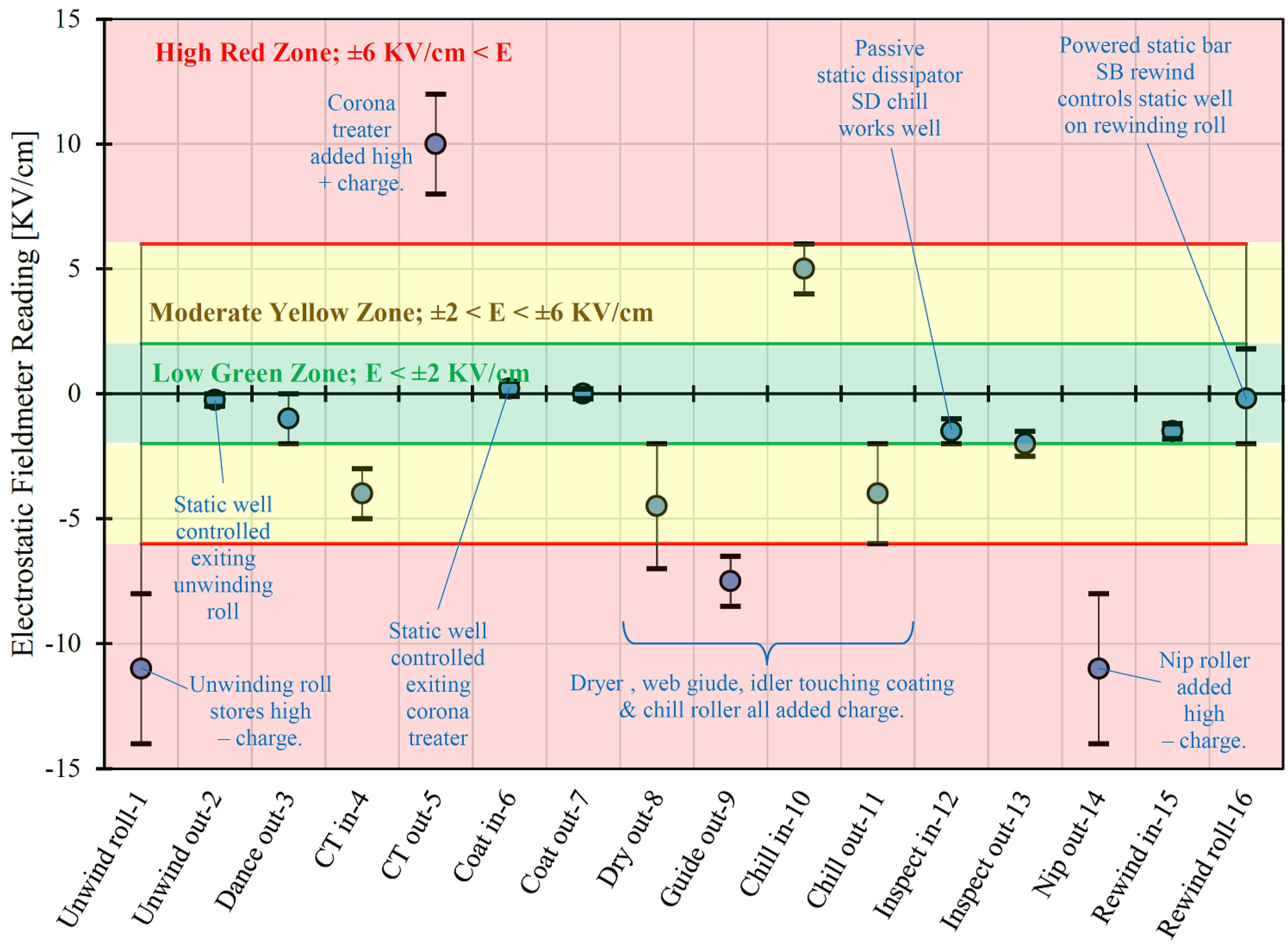

Fig. 7. The stop-light chart of the average, minimum, and maximum fieldmeter readings summarizes the static performance.

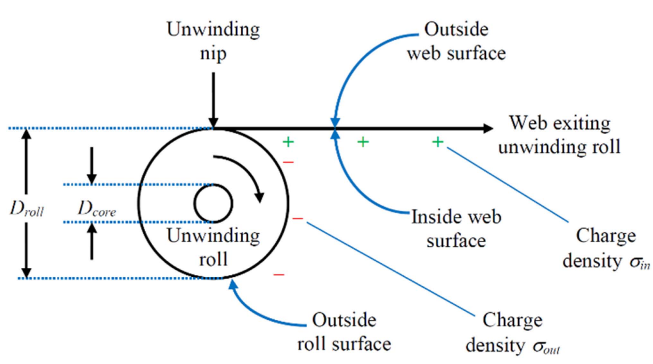

Fig. 8. The inside surface of the exiting web peels from the outside surface of the unwinding roll at the unwinding nip.

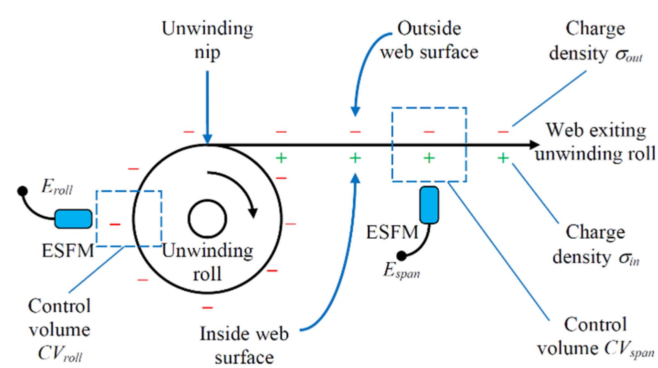

Fig. 9. In steady state, tribocharging at the unwinding nip results in the roll being charged while the exiting web carries balanced charges.

However, I reach a different conclusion based on many measurements and the following analysis. Suppose the web in Fig. 11 enters with charge density σ_{top} on the top surface, and σ_{bot} on the bottom surface. The charge densities on the incoming web are measured as in Fig. 1 by E_{in} and $V_{top\text{-}in}$. E_{in} responds to the charges represented by two + symbols in control volume CV_{in}. $V_{top\text{-}in}$ responds to σ_{top} on the exposed, top surface of the web.

Powered static bar $\mathrm{SB_{bot}}$ responds to the static charges inside control volume CV_{in} represented by two + symbols. $\mathrm{SB_{bot}}$ provides two, opposite polarity ions represented by two – symbols. The result is that the web exits CV_{in} with zero net charge. The charge density σ_{top} on the top surface is unchanged by $\mathrm{SB_{bot}}$ while σ_{bot} is changed by the neutralizing negative ions provided by SB_{bot}. The web exits CV_{in} with charge density σ_{bot} that is equal in magnitude and opposite in polarity to σ_{top}.

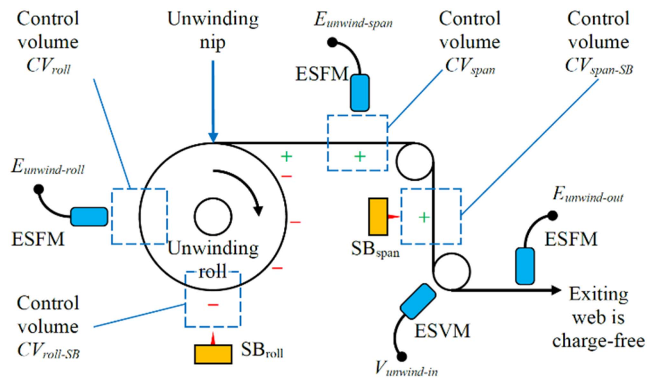

Fig. 10. Charges on both surfaces of the web exiting the unwinding roll are neutralized by powered static dissipaters $\mathrm{SB}_{\mathrm{roll}}$ and $\mathrm{SB}_{\mathrm{span}}$.

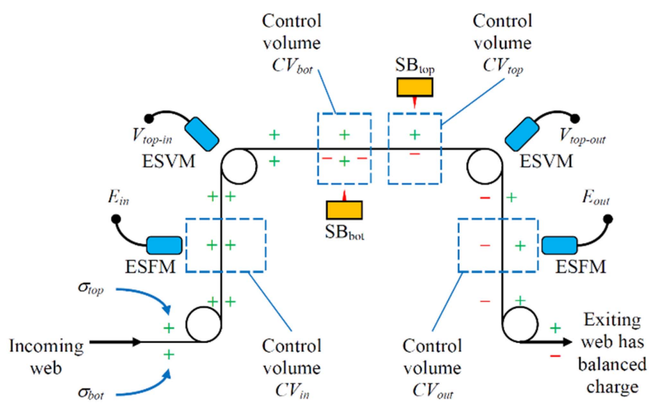

Fig. 11. Static dissipater $\mathrm{SB}_{\mathrm{top}}$ is ineffective. The exiting web carries static.

The web now enters control volume CV_{top} with zero net charge. Powered static bar SB_{top} responds to the net charges inside CV_{top}, which are zero. Consequently, SB_{top} provides no neutralizing ions. The charge densities on the web exiting CV_{top} are unchanged by SB_{top}. So, SB_{top} may be removed from this web span and used elsewhere on the line to improve static performance.

I have confirmed the operation of static bars $\mathrm{SB}_{\mathrm{bot}}$ and $\mathrm{SB}_{\mathrm{top}}$ many times by static surveys performed at client sites. These static surveys include ESVM reading $\mathrm{V}_{\mathrm{top\text{-}out}}$ and ESFM reading E_{out} in Fig. 11 that I use to determine the charge densities on both surfaces of the exiting web as in Fig. 1.

B. Nip Roller

Nip rollers are commonly used in R2R manufacturing lines to control web tension and ensure high traction for driven rollers. The polymer covered nip roller in Fig. 12 can deposit a large amount of static on a web while the metal or hard-coated aluminum nip roller deposits very little static. I have verified the charging caused by polymer nip roller by many measurements in static survey at customer sites.

The best practice is to neutralize static on the web exiting the nip roller in Fig. 12 with static dissipater $\mathrm{SB}_{\mathrm{nip}}$ facing the web

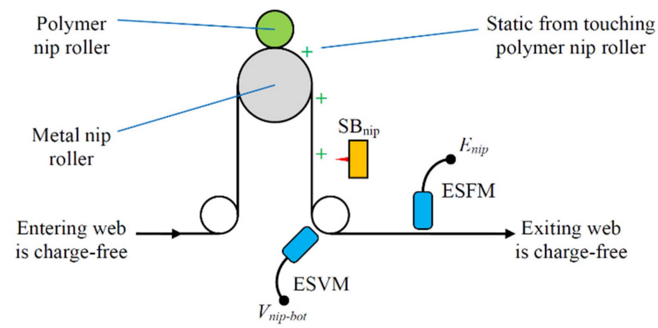

Fig. 12. Static dissipater $\mathrm{SB}_{\mathrm{nip}}$ neutralizes static from the polymer nip roller.

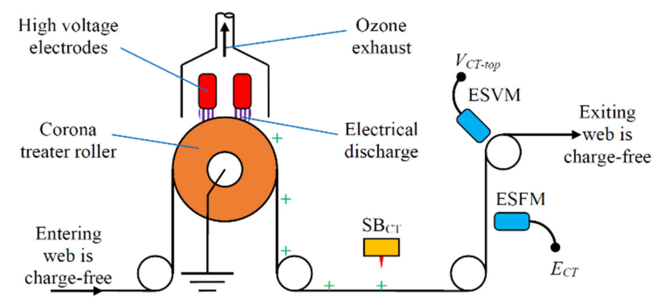

Fig. 13. Static dissipater $\mathrm{SB}_{\mathrm{CT}}$ neutralizes static from the corona treater.

surface that touched the polymer nip roller because this web surface gained charge when it touched the polymer roller.

Static control performance may be verified by $V_{nip,bot}$ and E_{nip}. The charge densities on both web surfaces exiting the nip roller in Fig. 12 are measured as in Fig. 1 to verify that $\mathrm{SB}_{\mathrm{nip}}$ neutralizes static from touching the polymer nip roller and that static remains low on the web surface that touched the metal nip roller.

C. Corona Treater

Corona treaters are used in R2R manufacturing operations prior to coating or printing to improve wettability and prior to lamination to improve adhesion. The corona treater in Fig. 13 has a grounded treater roller that can be bare metal, polymer covered, or ceramic covered roller. High voltage commonly 10–20 kV at 10–20 kHz is applied to high-voltage electrodes mounted close the treater roller causing an energetic electrical discharge between the electrodes and the web wrapped on the grounded treater roller. This discharge incorporates new chemical species into the polymer. This surface chemistry modification results in improved wettability and adhesion.

Unwanted by-products of corona treatment are ozone, which is captured and exhausted by air-handling ducts, and electrostatic charges deposited on the treated surface. The best practice is to neutralize static on the web in Fig. 13 exiting the corona treater using static dissipater $\mathrm{SB}_{\mathrm{CT}}$ facing the treated surface.

Static control performance exiting the corona treater in Fig. 13 is verified by determining the charged densities on both web surfaces as in Fig. 1 from $V_{CT\text{-}top}$ and E_{CT}. $V_{CT\text{-}top}$ verifies that static dissipater $\mathrm{SB}_{\mathrm{CT}}$ neutralizes static on the treated surface

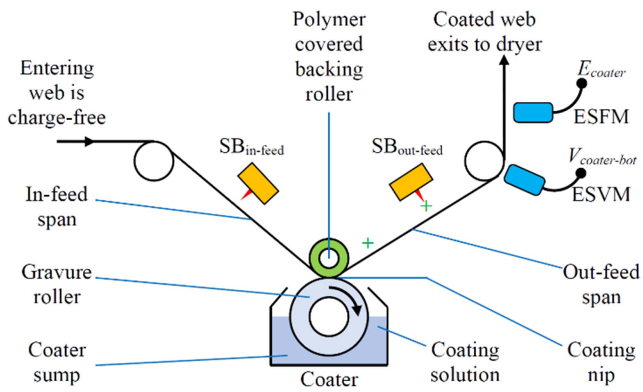

Fig. 14. SB$_{\text{in-feed}}$ protects the coater from upstream sources of static. SB$_{\text{out-feed}}$ neutralizes static on the web from touching the backing roller.

from the corona treater. E_{CT} verifies that net charge the web exiting the corona treater is low

D. Gravure Solvent Coater

Gravure coaters are widely used because they can print high quality graphics and coat webs at high speeds up to 1000 m/min [11]. The gravure roller in Fig. 14 has small pits or cavities that fill with coating solution in the sump of the coater. The gravure roller carries the coating solution to the coating nip where the web is pressed against the gravure roller by the backing roller. The coating solution transfers to the web, which exits the coating nip to a dryer.

The gravure coating solution often contains a solvent that is easily ignited by a static spark. The best practice for preventing ignitions in the solvent coater in Fig. 14 has three elements: SB$_{\text{in-feed}}$, SB$_{\text{out-feed}}$, and a static dissipative backing roller.

Static dissipater SB$_{\text{in-feed}}$ on the in-feed web span entering the coating nip in Fig. 14 is a failsafe dissipater that protects the high-risk solvent coater from static deposited on the web by upstream charging sources. SB$_{\text{in-feed}}$ is normally located above the web facing the back, uncoated side of the web to protect it from being splashed and contaminated by coating solution.

SB$_{\text{out-feed}}$ on the out-feed web span in Fig. 14 neutralizes static on the web surface that touched the backing roller. In normal operation, the electric field on the out-feed span is zero because the coating solution is somewhat conducting. However, when coating stops, which occurs routinely at the end of a coating run and in an unusual event such as a web-break or a coating pump failure, which allows the coater to run dry, the uncoated outfeed web span can be charged by touching the backing roller. SB$_{\text{out-feed}}$ prevents ignitions from the uncoated web on the out-feed span.

The polymer covered backing roller in Fig. 14 presses the web against the gravure cylinder. The roller surface becomes charged by touching the uncoated web surface. If enough charges accumulate on the roller surface, a spark occurs typically near the end of the roller to the exposed roller metal core.

Charge on the backing roller surface must be dissipated to prevent these sparks, which can ignite flammable solvent vapors. While static dissipaters may be used to dissipate static on the backing roller, the best practice is to use a static dissipative backing roller. The charge relaxation time τ_e in (9) is proportional to the volumetric resistivity.

$$\tau_e = \varepsilon_0 \kappa_r \rho_{r-vol} \tag{9}$$

The maximum volumetric resistivity $\rho_{r\text{-}vol\text{-}max}$ of the polymer or rubber covering on the backing roller in (10) is determined by requiring that 95% of the charges dissipate ($3\tau_{\text{e}}$) in one revolution of the backing roller.

$$\rho_{r-vol} = \frac{\pi D_{roller}}{3\varepsilon_0 \kappa_r U_{line}} \tag{10}$$

The maximum volumetric resistivity of the polymer or rubber covering on the backing roller is plotted in Fig. 15 as a function of line speed U_{line} and backing roller diameter D_{roller}. For example, for a line speed U_{line} of 600 ft/min and 4-inch diameter backing roller, $\rho_{r\text{-}vol\text{-}max}$ is $1\times10^{+9}$ Ω-m.

Static performance is verified by $V_{coater\text{-}bot}$ and E_{coater} in Fig. 14, which determine the charge densities on both web surfaces exiting the coater as in Fig. 1. $V_{coater\text{-}bot}$ and E_{coater} are typically taken during a conveyance trial with no coating solution present and the backing roller spaced a small distance away from the gravure roller. E_{coater} verifies that SB$_{\text{out-feed}}$ neutralizes static from the backing roller. $V_{coater\text{-}bot}$ verifies that the coated side of the web enters the coater with low charge.

E. Chill (or Heated) Roller

Chill rollers and heated rollers are used to change the temperature of webs. The chill roller in Fig. 16 can deposit a significant amount of static on the web. I speculate that charging occurs when the web experiences microslip against the thermal transfer roller. With the web in close contact with the roller, the web dimensions change with its temperature while the roller dimensions remain nearly constant. The temperature of the metal, thermal transfer roller is nearly constant.

The best practice is to dissipate static on the web exiting the chill roller in Fig. 16 using static dissipater SB$_{\text{chill}}$ facing the web surface that touched the roller.

Static control performance may be verified by measuring the charge densities on both web surfaces exiting the chill roller in Fig. 16 by $V_{chill\text{-}bot}$ and E_{chill}. $V_{chill\text{-}bot}$ verifies that SB$_{\text{chill}}$ neutralizes static from the chill roller by taking one reading with SB$_{\text{chill}}$ turned off and a second reading with SB$_{\text{chill}}$ turned on. E$_{\text{chill}}$ ensures that net charge on the web exiting the chill roller is low.

F. Tacky Web Cleaning Roller

Web cleaners remove dirt and particles that contaminate webs. While cleaners using high velocity air or a rotating brush can remove particles having diameters larger than about 20 μm, removing smaller particles requires touching the web with a tacky, cleaning roller. These tacky rollers can deposit large amounts of static on webs. When cleaning both sides of a web, I advocate using S-wrapped cleaning rollers illustrated in Fig. 17 rather than two, nipped cleaning rollers. Nipped cleaning rollers

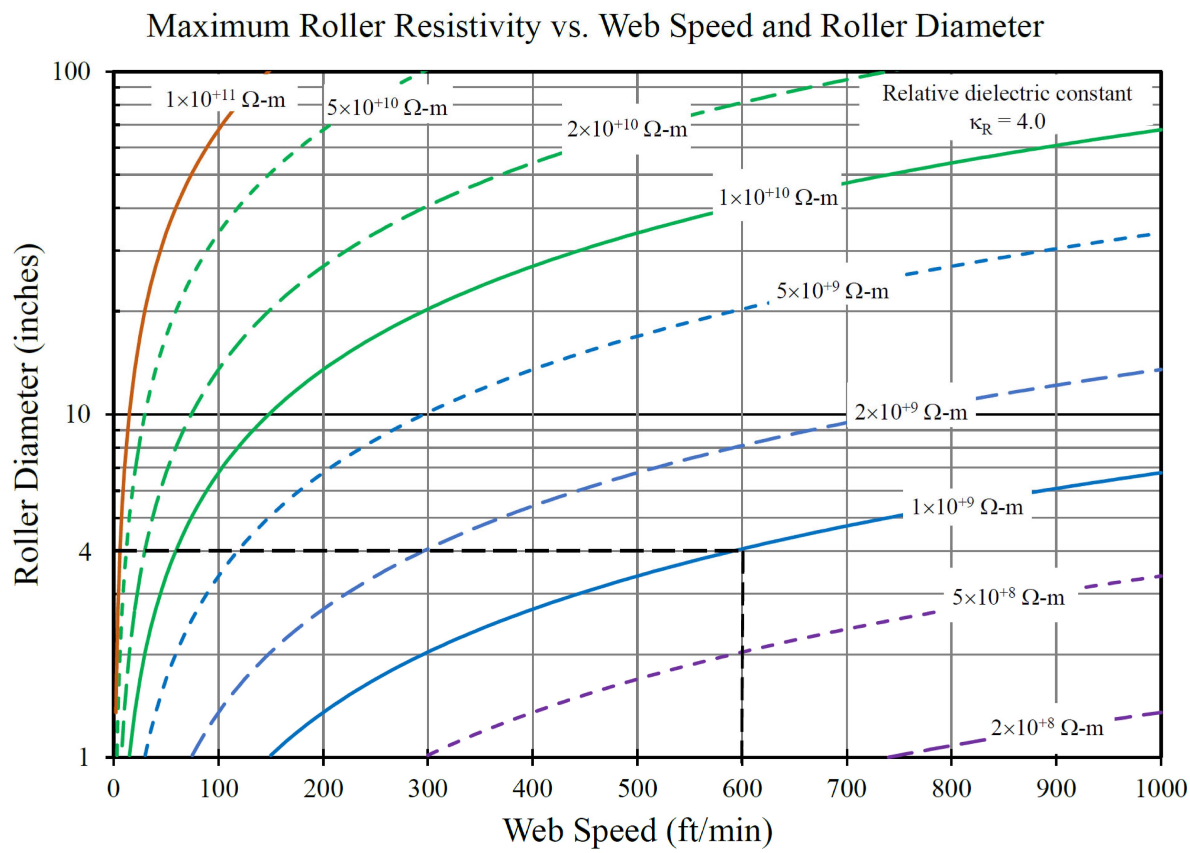

Fig. 15. The maximum volumetric resistivity of the polymer or rubber cover on the backing roller varies with web speed and roller diameter.

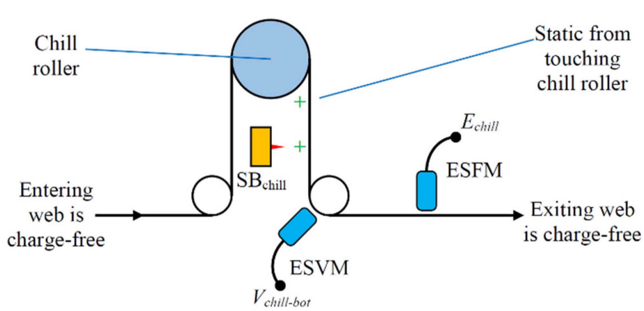

Fig. 16. SB_{chill} neutralizes static from the chill roller.

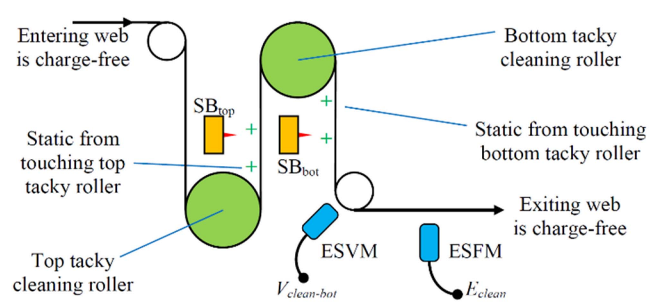

Fig. 17. SB_{top} and SB_{bot} neutralize static from the tacky cleaning rollers.

deposit charges simultaneously on both web surfaces, which complicates static charge control.

The best practice is to dissipate static on the web exiting each tacky roller in Fig. 17 with a static dissipater facing the web surface that touched the roller. SB_{top} neutralizes static from the top cleaning roller. SB_{bot} neutralizes static from the bottom cleaning roller.

Static control performance may be verified by measuring the charge densities on both web surfaces exiting the tacky, cleaning rollers in Fig. 17 by $V_{clean\text{-}bot}$ and E_{clean}. $V_{clean\text{-}bot}$ verifies that SB_{bot} neutralizes static from the bottom cleaning roller. E_{clean} ensures that net charge on the web exiting the cleaning rollers is low.

G. Spreader Roller

The spreader roller in Fig. 18 eliminates wrinkles and creases by making sliding contact to widen the web by pushing material towards the edges. Spreader rollers have many names including bowed rollers, banana rollers, and Mt. Hope rollers. This sliding contact between the roller and the web surface can deposit a significant amount of static on the web.

The best practice is to dissipate static on the web exiting the spreader roller in Fig. 18 using static dissipater SB_{spread} facing the web surface that touched the spreader roller.

Static control performance is verified by measuring the charge densities on both web surfaces exiting the spreader roller in Fig. 18 by $V_{spread\text{-}bot}$ and E_{spread}. $V_{spread\text{-}bot}$ verifies that

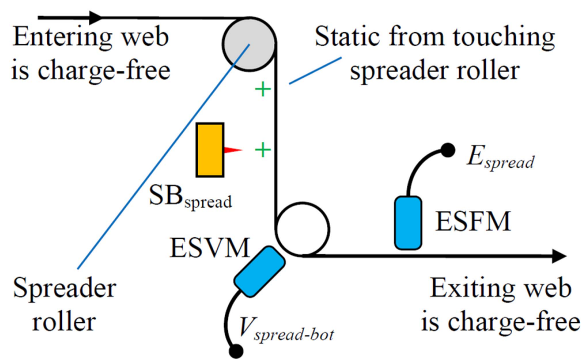

Fig. 18. SB$_{\text{spread}}$ neutralizes static from the spreader roller.

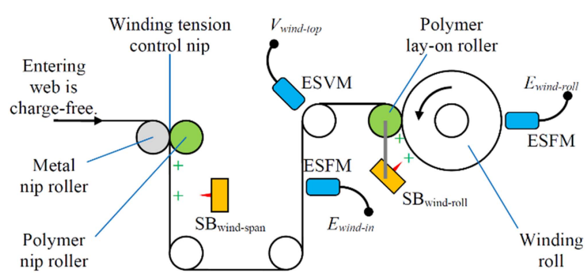

Fig. 19. SB$_{\text{wind-span}}$ neutralizes static from the tension control nip. SB$_{\text{wind-roll}}$ neutralizes static on the winding roll from touching the polymer lay-on roller.

SB$_{\text{spread}}$ neutralizes static from the spreader roller. E$_{\text{spread}}$ ensures that net charge is low on the exiting web.

H. Winding Roll

The over-arching static control goal is for the web entering the winding roll in Fig. 19 be charge-free. Static must be well controlled upstream so that the web entering the tension control nip is charge-free. The tension control nip deposits static on the web surface that touches the polymer nip roller as discussed in *B. Nip Roller*. SB$_{\text{wind-span}}$ neutralizes static on the web from touching the polymer nip roller.

Many winders use the lay-on roller in Fig. 19 to improve wound roll integrity. This polymer lay-on roller deposits static on the outside surface of the winding roll. Static dissipater SB$_{\text{wind-roll}}$ neutralizes static on the outside surface of the winding roll from touching the lay-on roller. The diameter of the winding roll increases as the roll builds. Attaching the mounting bracket for SB$_{\text{wind-roll}}$ to the frame of the lay-on roller enables SB$_{\text{wind-roll}}$ to move with the lay-on roller as the winding roll builds. The constant distance from SB$_{\text{wind-roll}}$ to the winding roll maintains neutralization efficiency.

For winders that do not use a lay-on roller, SB$_{\text{wind-roll}}$ may be mounted at a fixed location so that it is spaced approximately 6 inches from a full, maximum diameter, wound roll. This fixed static dissipater must be a high performance, long-range, pulsed DC static bar that can have good neutralizing efficiencies at distances exceeding 0.5 meter [9]. And, SB$_{\text{wind-roll}}$ mounted in a fixed position should be mechanically guarded to prevent damage if a roll is dropped by accident.

TABLE II
3 Fit-for-Use Criteria

1.	In place and properly spaced.
2.	Clean.
3.	Power applied.

The over-all static performance of the line may be verified by $V_{wind\text{-}top}$, $E_{wind\text{-}in}$ and $E_{wind\text{-}roll}$ in Fig. 19. $V_{wind\text{-}top}$ and E_{wind} are used as in Fig. 1 to find the charge densities on both web surfaces entering the winding roll. $E_{wind\text{-}in}$ also verifies that SB$_{\text{wind-span}}$ neutralizes static from touching the polymer nip roller. $V_{wind\text{-}top}$ verifies that the top surface of the web entering the winding roll is charge-free. $E_{wind\text{-}roll}$ verifies that SB$_{\text{wind-roll}}$ neutralizes static from the lay-on roller. Also, E$_{\text{wind-roll}}$ verifies that the winding roll stores little static.

V. Maintain Static Performance

Static problems occur when two elements in the fault-tolerant static control system fail simultaneously. Process monitoring must detect a failure and system maintenance must restore operation of the failed component before two failures occur.

A. Fit-for-Use Inspections

Make a checklist of each static dissipater on a line including a photo of the device when it is properly installed. During preparations for a job, an operator should walk the line and visually inspect each static dissipater to ensure that it is “fit-for-use.” Being fit for use means that each dissipater meets the three criteria in Table II. Static dissipaters are often removed from the machine to enable access for cleaning and for maintenance. The fit-for-use inspection verifies that each static dissipater has been reinstalled, properly oriented and spaced from the web. Dissipaters must be clean to function properly. A fit-for-use inspection verifies that each dissipater is visually clean. Finally, power must be applied to powered static bars. Overlooking this vital step has caused costly problems. My experience is that these simple, fast, fit-for-use inspections prevent many system failures.

B. Periodic and On-line Static Measurements

Identify a few, key locations to regularly take hand-held ESFM readings. Take three to five static readings periodically (weekly or bimonthly) to verify that the static control system is functioning properly. Key locations are entering high-risk areas (coaters, winding rolls) and exiting known sources of static charging (nips, corona treaters, dryers, spreader rollers, chill rolls, heated rolls). These readings may be plotted on a control chart to monitor static performance.

Electrostatic fieldmeters designed to be permanently installed in manufacturing lines are commercially available. On-line monitors are a good method to track static performance and detect failures.

C. Static Surveys

A static survey provides detailed, granular information on the static performance of a machine. A static survey may be completed during normal production or during a conveyance trial when there is, for example, no coating applied. Conveyance trials are often run to verify tension controls, speed sensors, web handling, and other system components to qualify a machine for service after it has been shut down for maintenance. Qualify the static control system for service by including a static survey in these commissioning trials.

D. Management of Change (MoC)

Management of Change (MoC) is an administrative control procedure for safety, health, and environmental risks and hazards [12]. Facilities, operations, and personnel change often in manufacturing operations. Such changes may inadvertently introduce new risks and hazards into an operation. MoC policies identify these risks and hazards, and guard against introducing new hazards into the workplace. Include static control in assessments of changes when machines are upgraded or changed. For example, establish the baseline performance with a static survey prior to a change. Perform a second static survey after the change to verify that static is well controlled to qualify the machine for service.

VI. Summary

Static control is important for safety, product quality, and manufacturing productivity. Fault-tolerant static control maintains satisfactory static control even when any single system component fails. Fault tolerant control is achieved with minimally redundant static dissipaters. Since each static dissipater requires maintenance and performance verification, using fewer static dissipaters reduces the burden on operations. Use best-practice locations for static dissipaters. Maintain system performance by quick, fit-for-use inspections, periodic static measurements, and by including static performance in management of change procedures.

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