Evolving Design and Worker Electrical Safety Standards

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IEEE

Outline of Presentation

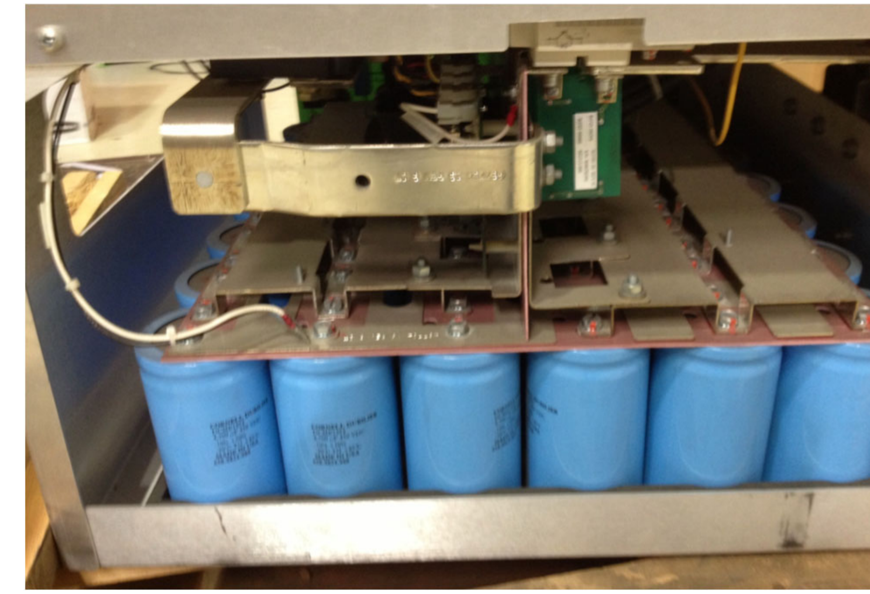
- New Technologies and Their Electrical Hazards
- DC and RF Hazards
- Why we Need Standards
- History of DC in the NEC
- History of DC Worker Safety
- Current and Evolving DC Design Standards
- Current and Evolving DC Worker Safety Standards
- The Future

New Technologies Using DC and RF

Rapidly Evolving Use of DC and RF

- Power Electronics
  - Energy conversion: dc to ac, dc to dc
  - Electric Vehicles
  - Variable Frequency Motors
- Battery Systems
  - Energy Storage
  - Standby Systems
  - Electric Vehicles
- Hypervelocity Transportation
- Photovoltaic Power (Solar)
- Capacitors and Super Capacitors
- Wireless Energy Transfer and Wireless Charging
- High Altitude, Orbital, Lunar and Martian Power Generation

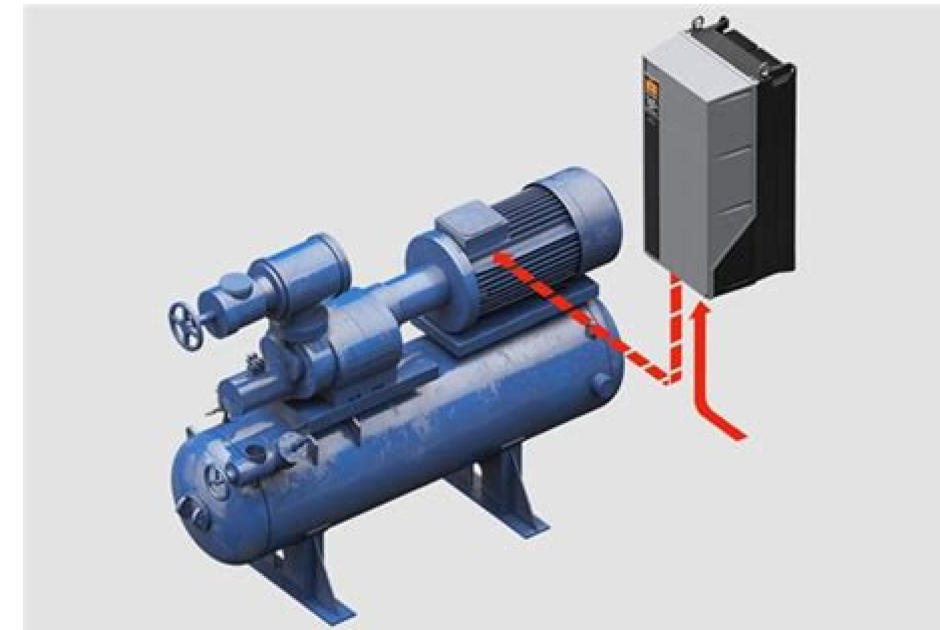
Power Electronics Safety Issues

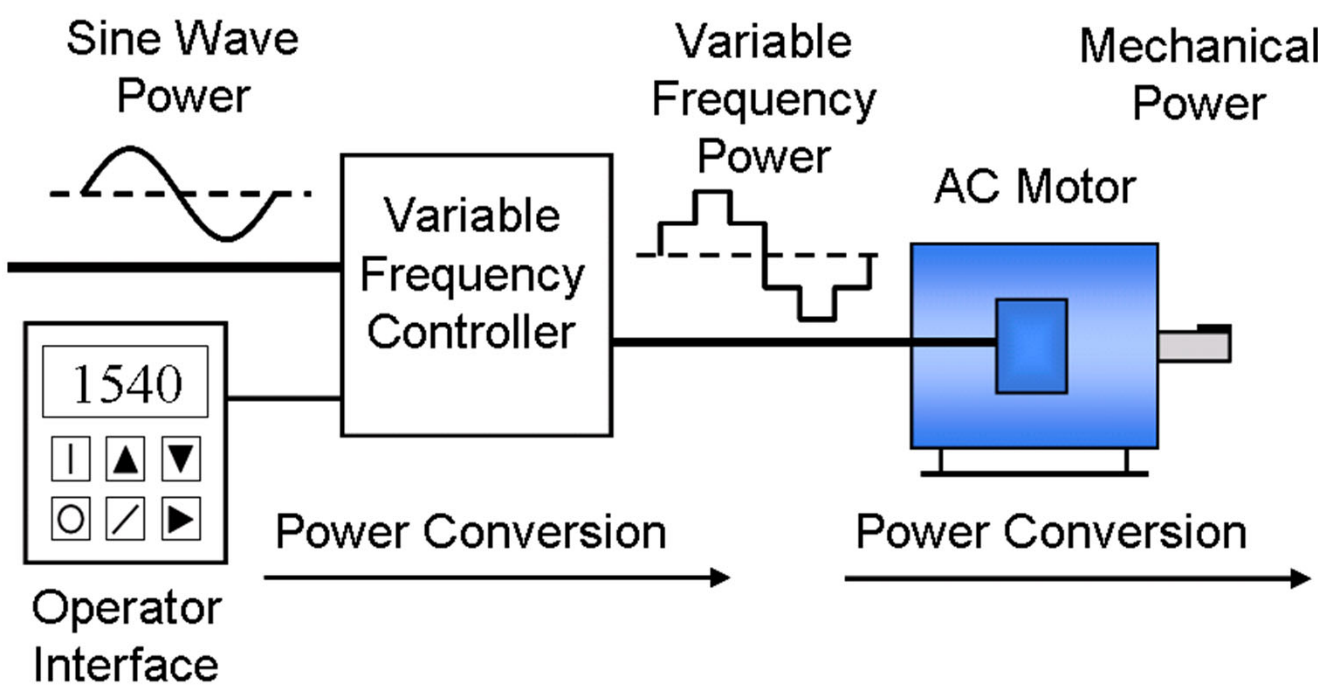


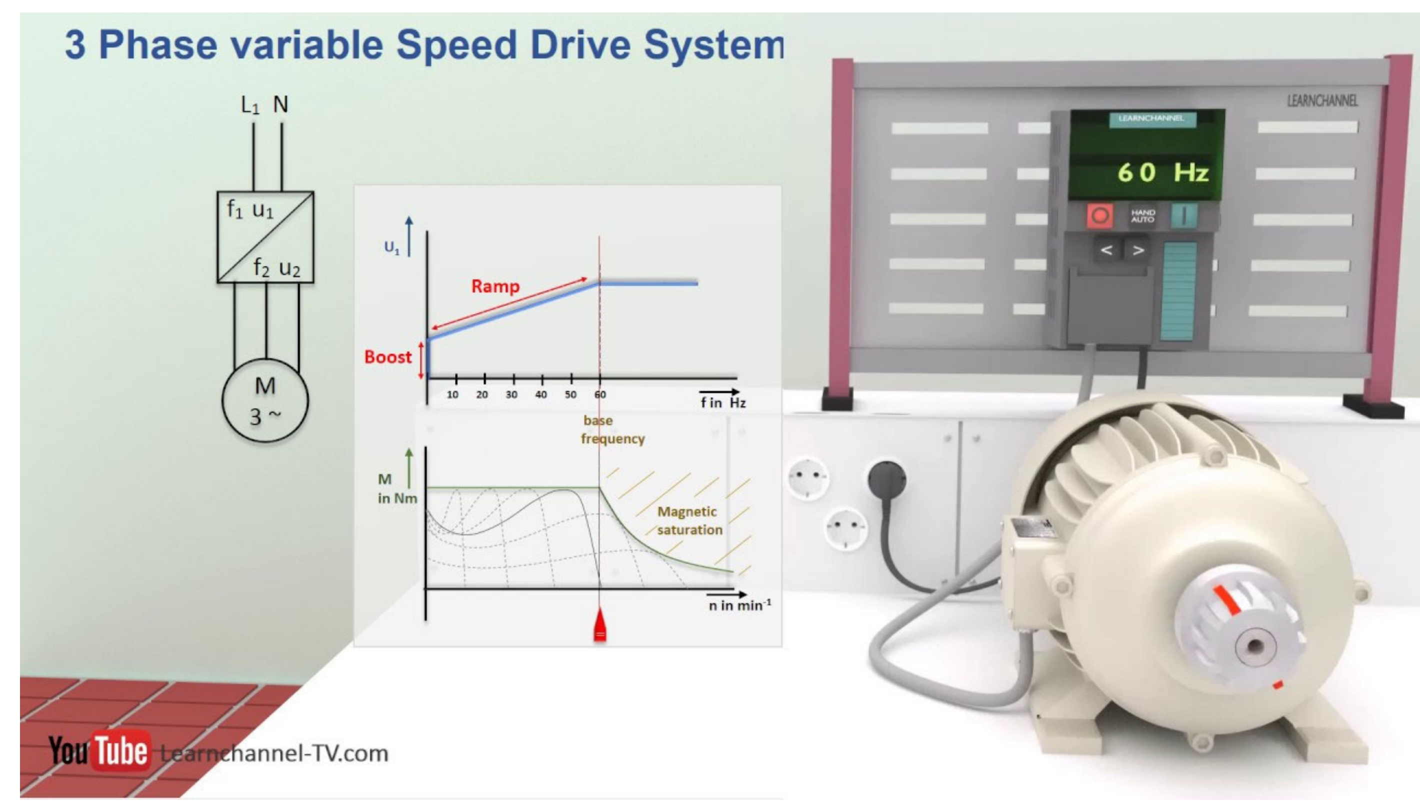
- Electrical Hazards
  - Thermal, shock, some arc flash
- Stored Energy:
  - Capacitors on DC Link
  - Test Before Touch
  - Capacitor failure
- Modulated Waveform
  - Unusual Output from VFD's
  - RF (3 kHz – 100 MHz) and sub RF (1 Hz – 3 kHz) hazards (shock and EM exposure)
  - Multimeters rated unfiltered for up to 10 kHz
- IGBT Block Failures
  - Failure modes can allow voltage on output

Variable Frequency Drives for motors (VFDs)

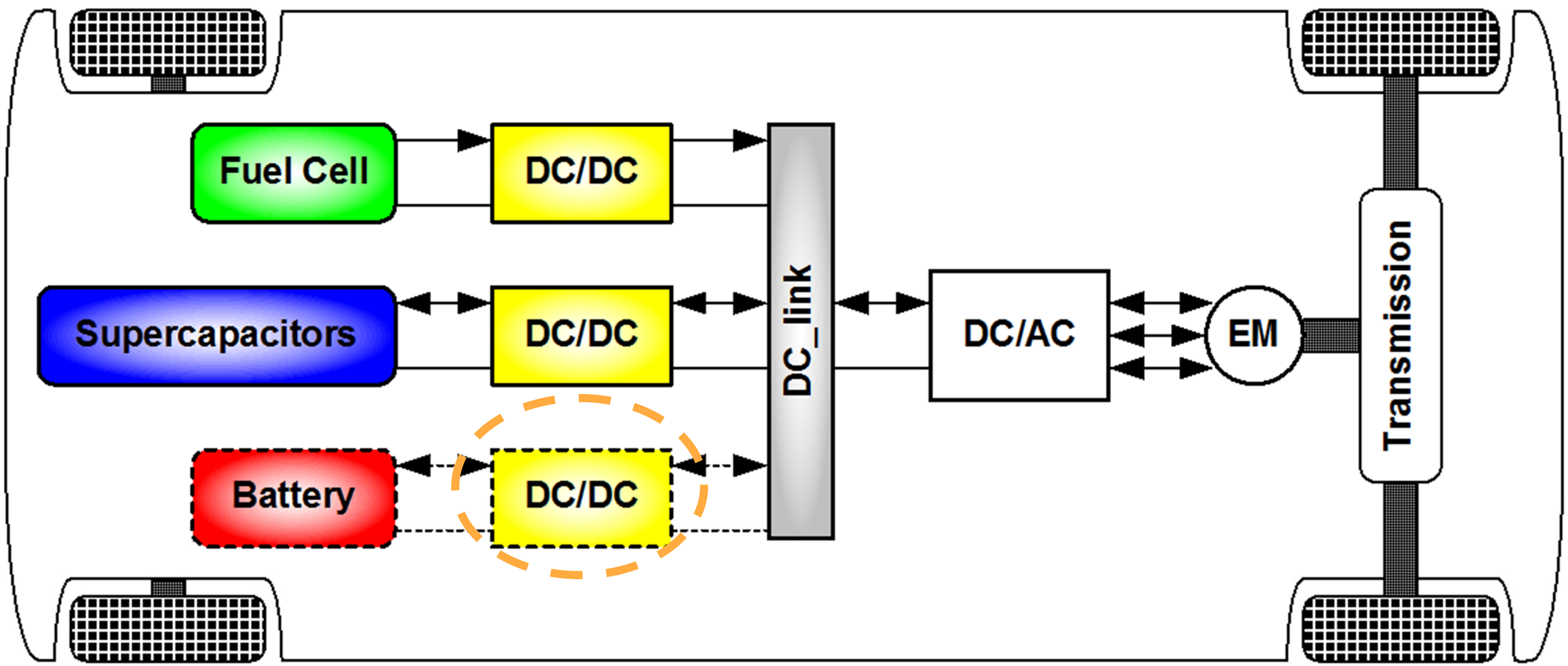
- Electrical Hazards
  - AC, DC, RF, subRF shock
  - Electromagnetic Fields (very little)
  - Arc Flash Hazards: AC yes, DC/output - unlikely



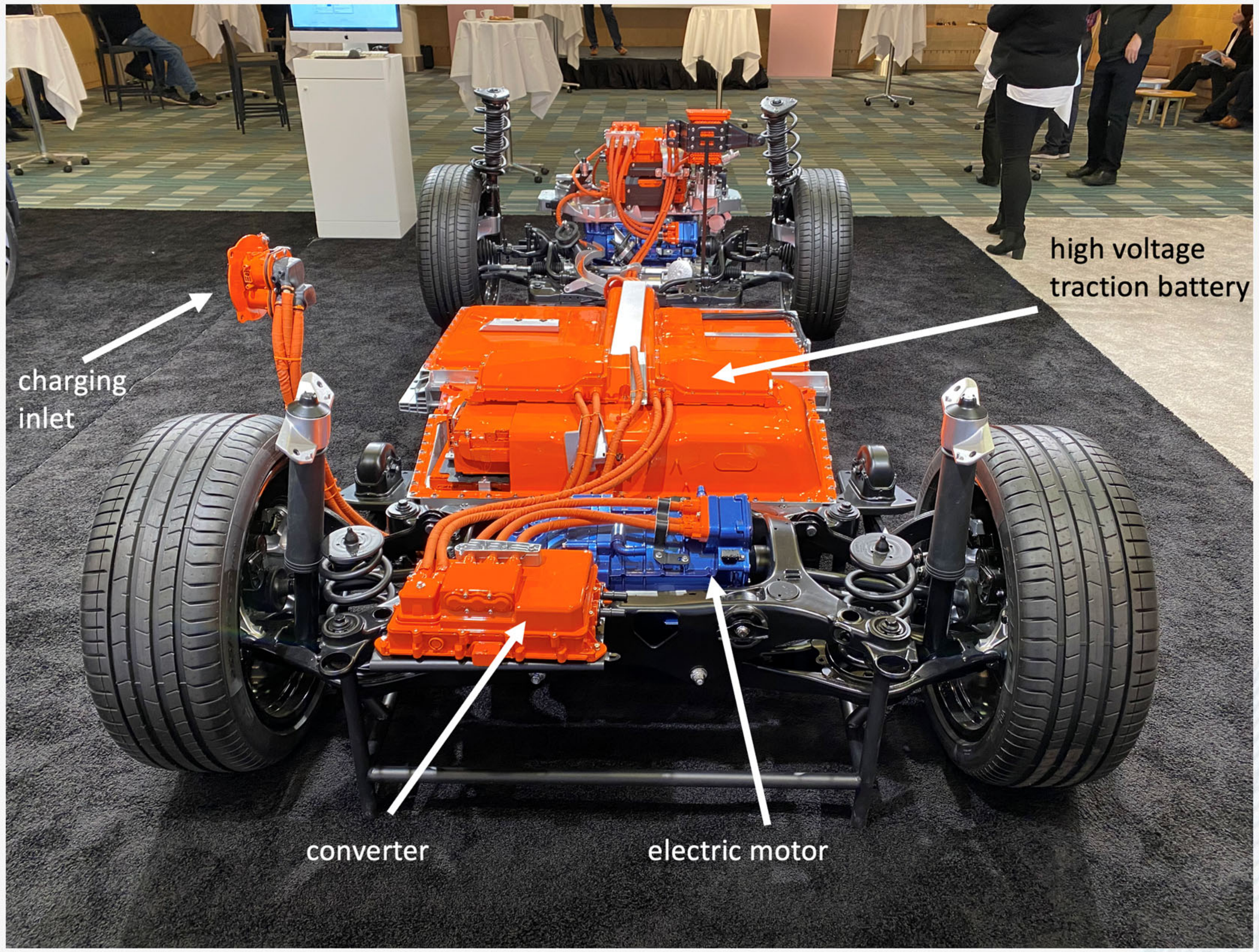




Example: Power Electronics in an EV



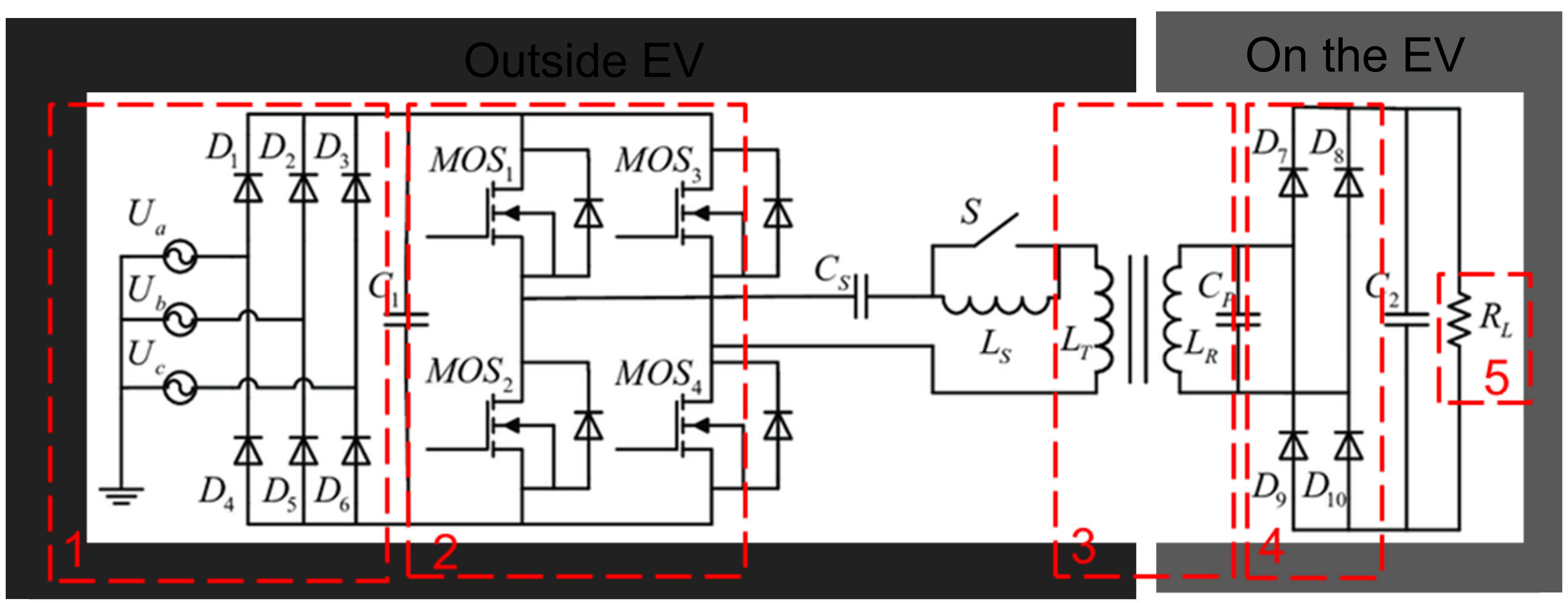
Electric vehicle HV batteries



	Battery voltage	Battery capacity	Battery pack weight
BEV	400–800 V	30–110 kWh	300–600 kg
PHEV	< 400 V	10–20 kWh	≈ 100 kg
Non-rechargeable HEV	< 400 V	≈ 1 kWh	≈ 20 kg

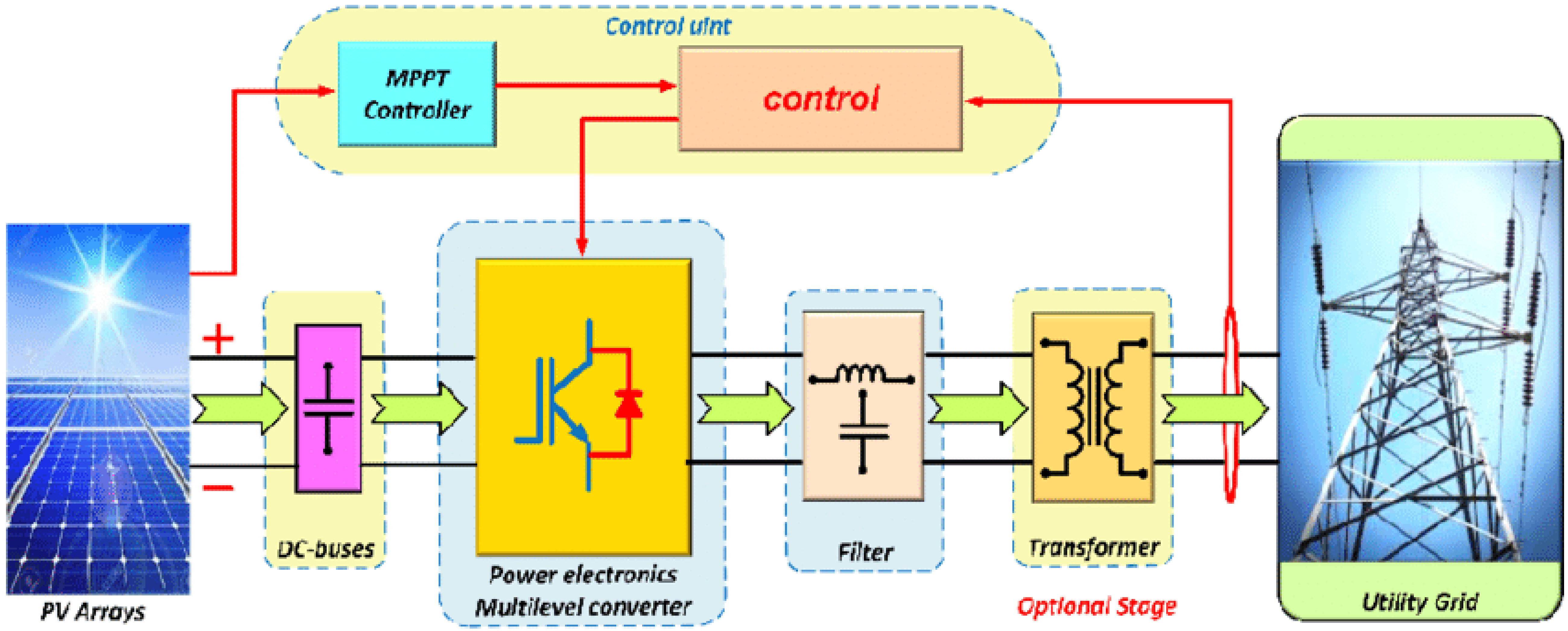
Wireless Charging in EVs

- Wireless Power Transfer (WPT) uses electromagnetic induction to induce a current in a receiving coil by means of an alternating magnetic field.
- An alternating magnetic field is generated by the flow of a "high" frequency AC current through a transmitting coil.
- No moving parts and can be fully automated



1. Three phase rectifier
2. High frequency inverter (DC/AC)
3. Air gap transformer = coil on the ground pad + coil on the EV
4. High frequency rectifier (AC/DC)
5. EV Battery

Typical schematic of a PV farm – grid connection



Bughneda, A.; Salem, M.; Richelli, A.; Ishak, D.; Alatai, S. Review of Multilevel Inverters for PV Energy System Applications. *Energies* **2021**, *14*, 1585. https://doi.org/10.3390/en14061585

Solar Power

- Electrical Hazards: thermal, shock, arc flash
- Solar power source NOT the same as Batteries or DC power supply outputs
- Always energized
- Constant current source
  - Short circuit current same as normal operating current

Solar Power near airport, Cali, Colombia

Battery Energy Storage Systems

- Up to 1,500 V, 400 MW, 1.6 GWhr – (e.g., CA, USA)
- Electrical Hazards: fire, thermal, shock, arc flash, chemical
- Always energized

Capacitors

- Found in rectifiers, invertors, energy storage, VFDs
- Electrical Hazards – thermal, shock, acoustic
- NFPA 70E, Article 360, Annex R

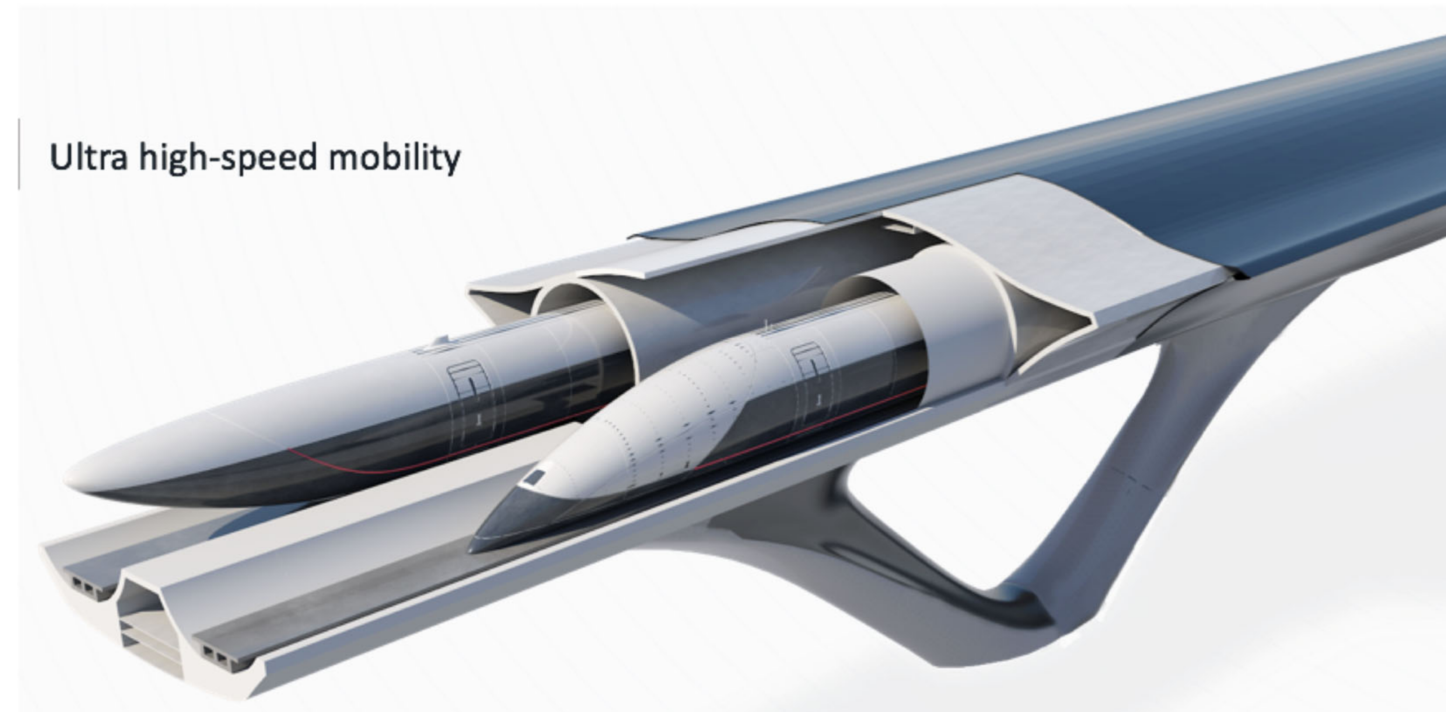
Super Capacitors

- Found in electric vehicles (e.g., starter batteries), energy storage, standby systems (wind turbines)
- Not a standard capacitor, not a battery
  - Characteristics between batteries and capacitors
- Hazards more similar to batteries
  - Thermal, shock, arc flash

Hypervelocity Transportation

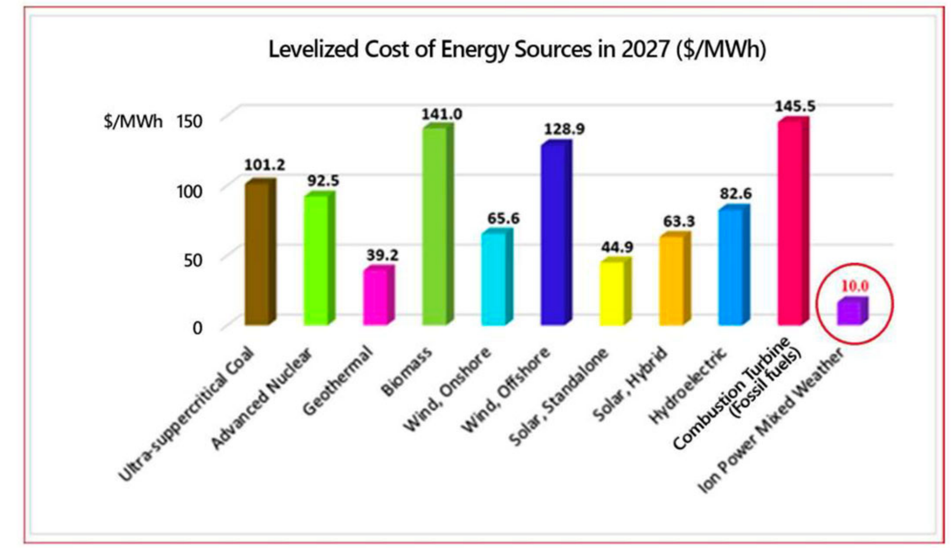
Vehicle Concepts

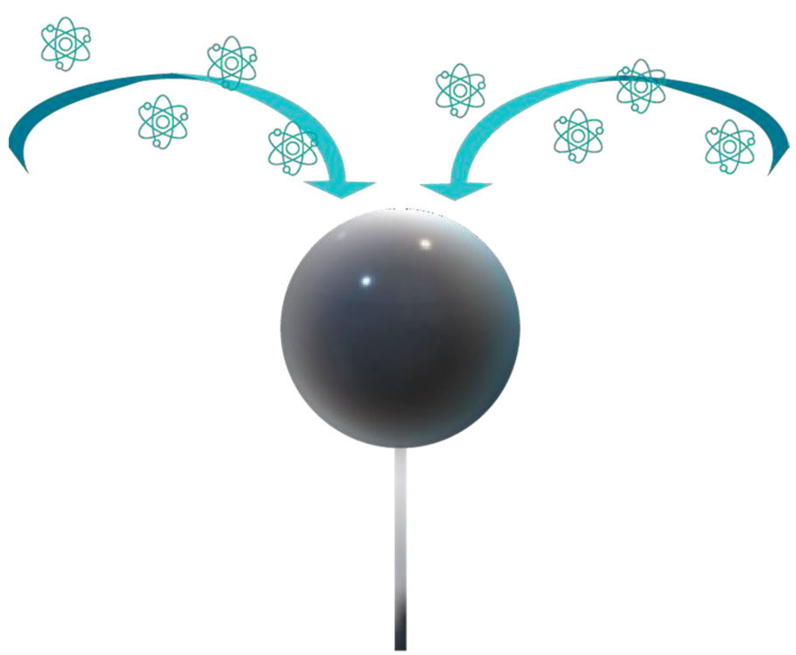
- ~ 500 mph
- Solar Arrays on Top
- Magnetic Levitation
- Evacuated Transport Tube
- Wireless Power Transfer
- On-board Battery Bank
- Rapid Charging



Very low cost power from High-Altitude Ion Harvesting

- High altitude aerostat (balloon) uses voltage gradient from upper atmosphere to earth to generate power
- 1/15 cost of fossil fuels, 1/5 cost of solar
- Night and Day generation
- Ion-harvesting aerostat brings 0.5 to 1 MV down to power processing station





Concepts for Power Generation at Extra Terrestrial Locations

- Lunar – harvesting solar generated near surface ions
- Martian – High altitude ion harvesting or wind-generated charge separation harvesting

DC and RF Electrical Hazards

DC Electrical Hazards

- Thermal
  - current through metal in contact with worker, close proximity to an arc
- Shock
  - contacting exposed, energized conductors
- Arc Flash
  - creating an arc in proximity to the worker
- Acoustic
  - creating a hazardous sound event
- Secondary - fire

Evolution of Worker Safety Standards

Rapid Evolution in DC Power

- In the past 20 years there has been a rapid growth of DC for electric power, facility and utility.
- This includes energy generation, storage, transmission, and utilization.
- Solar power generation, battery energy storage, distribution and transmission, power electronics, energy conversion, and electric transportation

- Standards are struggling to keep up.

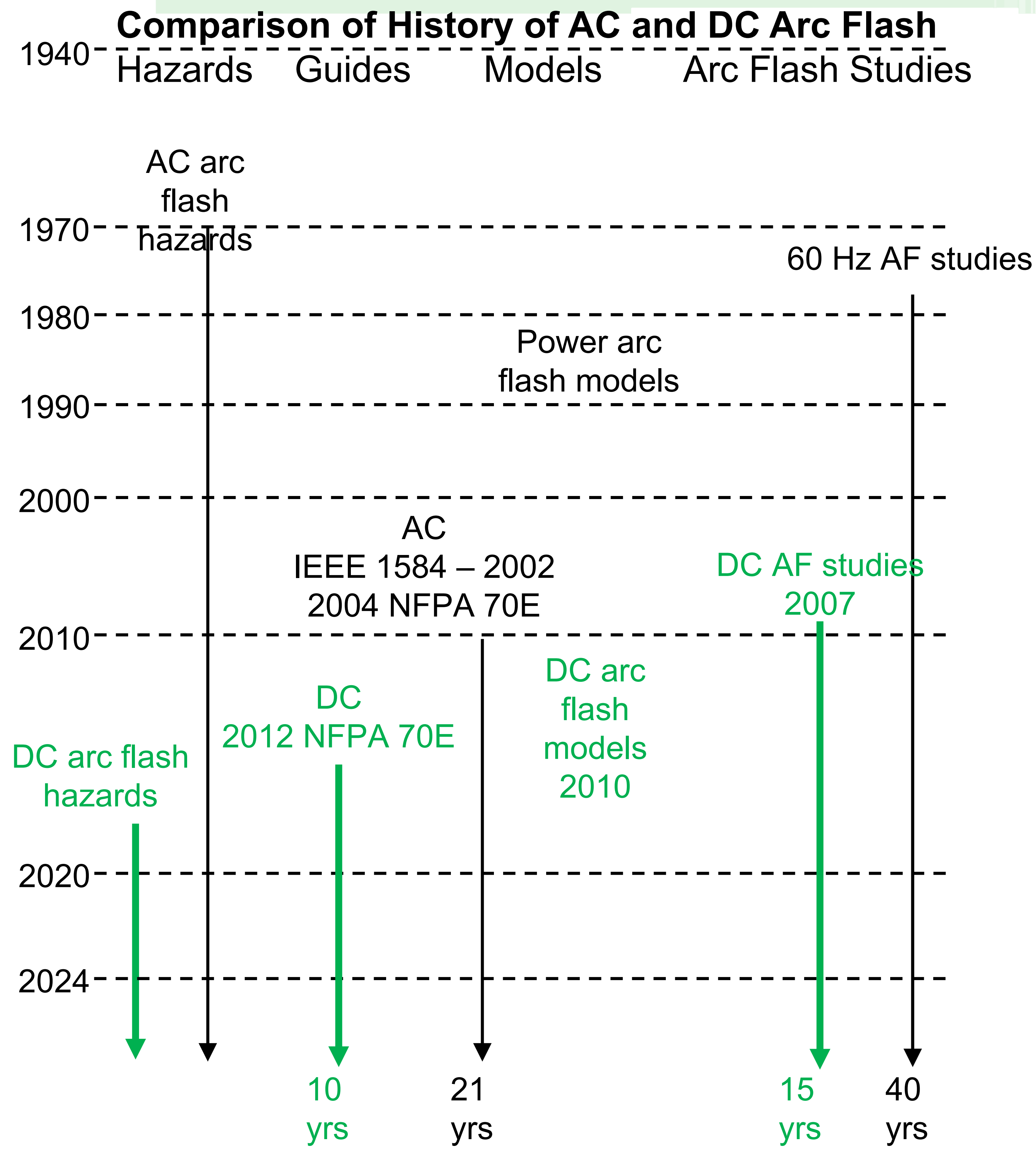
DC in the NEC (creation of new Articles) – an Installation Standard

Date	NEC Article	Topic	Date	70E Article	Topic
1950	480	Storage batteries, retitled Stationary Standby Batteries in 2023			
1980	668/669	Electrolytic Cells and Electroplating			
1984	690/705	Solar Photovoltaic Systems (small) and Interconnected Power Sources			
1996	625	Electric Vehicle Power Transfer System			
2002	692	Fuel Cell Systems	2000	310, 320, 330, 340	Cells, Batteries, Lasers, Power Electronics
2008	626	Electrified Truck Parking Spaces	2009	350	Laboratory Hazards
2011	694	Wind Electric Systems	2012	130 and Annex D	DC Shock and Arc Flash
2017	691	Large-Scale PV Electric Supply Stations			
2020	706/712	Energy Storage Systems / DC Microgrids	2021	360	Capacitors
2023	245/305	Protection/Wiring Methods for over 1000 Vac or 1500 Vdc	2024	Chapter 3 – Special Equipment	Added thermal, updated all DC, capacitor, RF and Sub RF

History of DC Hazards in Worker Safety Standards

- Shock Hazard
  - 2012 NFPA 70E – 100 V
  - Throughout Chapter 3 – Special Equipment
- Arc Flash Hazard
  - 2012 NFPA 70E – > 100 V
  - 2024 NFPA 70E – > 150 V
  - Task Tables
  - Annex D.5 – recommendations for analysis
- Thermal Hazard
  - 2024 NFPA 70E – 1000 W

- DC has been addressed in 70E for only 12 years

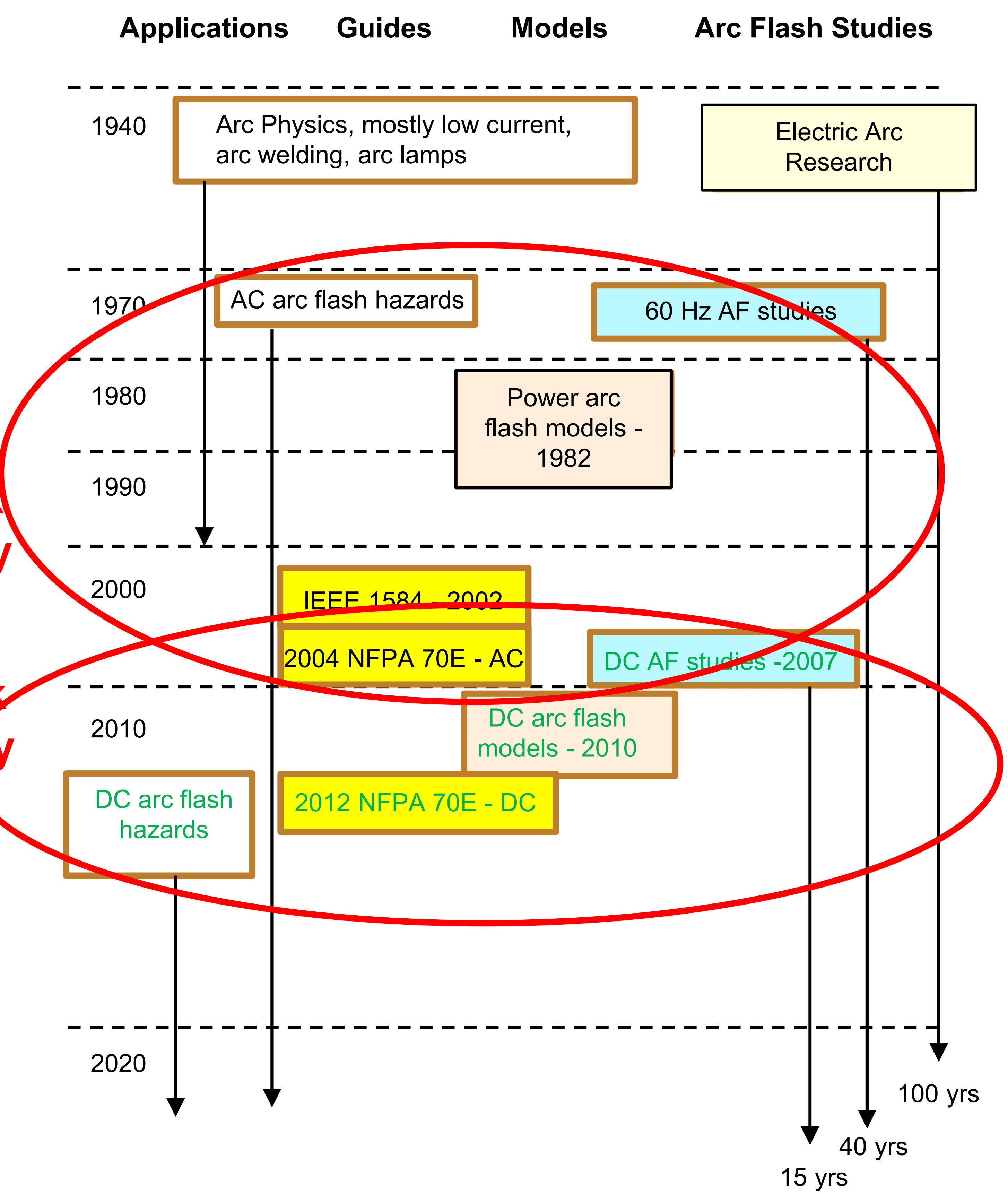


History of Arc and Arc Flash (AF) Research

- Electric Arc Research – > 100 years
  - Initially for welding and lighting
  - Later for arc flash hazards, la 50 years
- Arc Flash Measurements
  - AC 45 years
  - DC 15 years
- Arc Flash Models
  - AC - 40 years
  - DC - 10 years
- Arc Flash Guides
  - AC – IEEE 1584 (2002), NFPA 70E (2004)
  - DC – NFPA 70E (2012)

AC Arc Flash Work 1980 - today

DC Arc Flash Work 2007 - today



DC and RF Design and Safety Standards

Why Standards?

- Design standards provide
  - Equipment functionality and reliability
  - Protect equipment, environment and user
- Worker safety standards provide
  - Protection of worker, working on the equipment

Relationship Between Design and Worker Safety Standards

- Design must be considered for worker exposure to hazards.
  - Especially true for energized electrical work
    - *T-line hot work*
    - *Batteries (stationary and mobile)*
    - *Solar power*
- Risk Assessment for work must take design into consideration
  - Proper design reduces exposure

Risk assessment

An overall process that identifies hazards, estimates the potential severity of injury of damage to health, estimates the likelihood of occurrence of injury or damage to health, and determines if protective measures are required.

- Likelihood of occurrence is determined by:
  - *Work task and proximity to hazard,*
  - ***Engineering controls*** *that prevent exposure, or reduce consequence, and*
  - *Human performance*

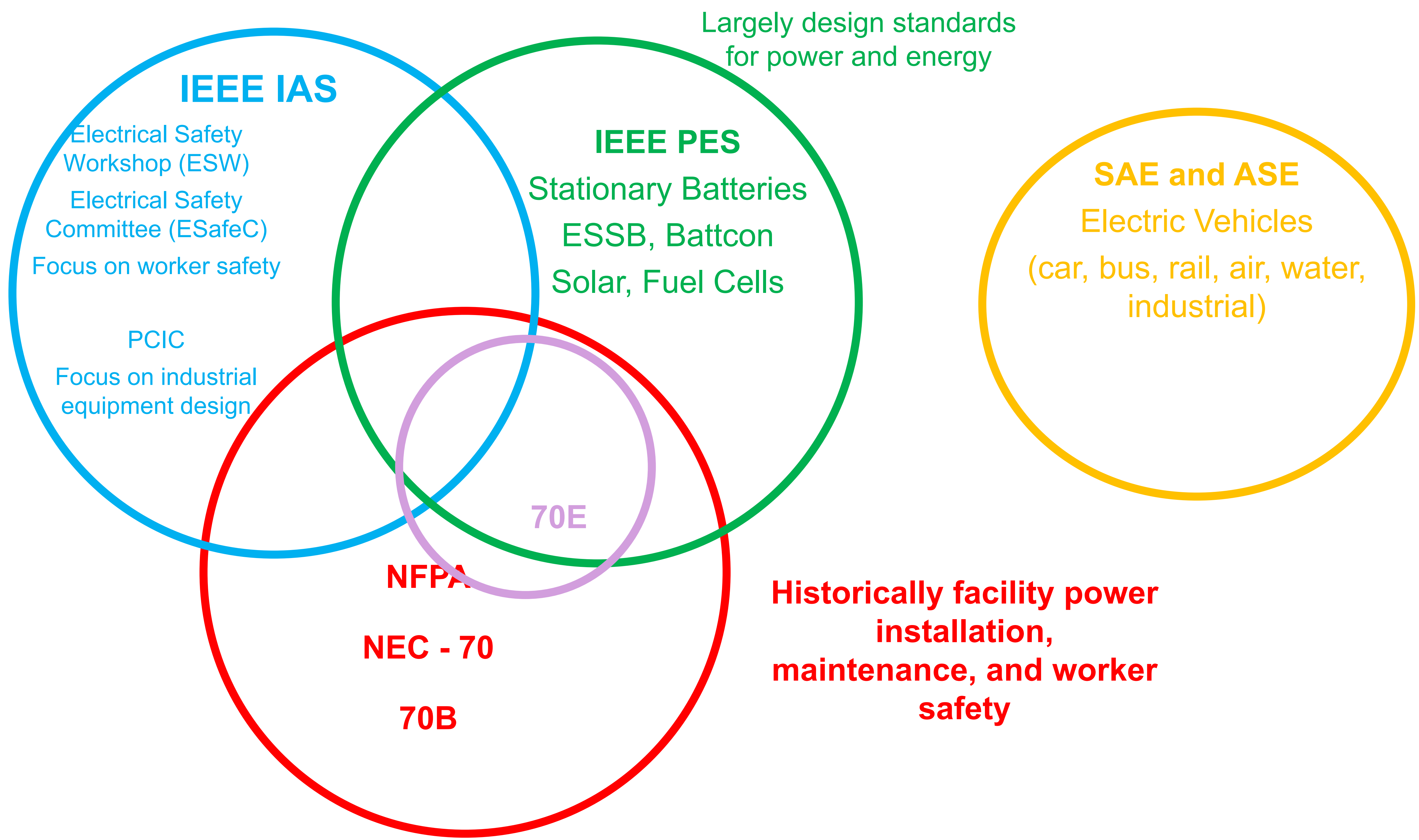
Hierarchy of Risk Control Methods

- Eliminating the hazard
- Substituting other materials, processes, or equipment
- Using engineering controls
- Warnings, barricades
- Administrative controls: training, procedures
- Using PPE

IEEE, NEC, UL, etc.
Design Codes and Standards

NFPA 70E and IEEE
Risk Assessment
Safety Standards

Synergism between Standards Organizations



Other standards not shown here

UL

IEC

other international

Relationship between Design Standards and Safe Work Practice Standards

- Implementation of Engineering Controls
  - *Driven by Design Standards*
- Reduces exposure to hazards, thus reducing risk to the public, infrastructure and worker
  - Reducing needs for administrative controls

Summary of **Design** and Worker Safety Standards

Source of Code/Standard	Design to protect equipment/user/worker	Worker Safety Standard
UL	Many – 10s	0
NFPA	NEC (70), 855 (Energy Storage)	1 – NFPA 70E -
IEEE	Many – NESC (utility), 100+	2 – IEEE 1584, NESC (utility)
SAE	Some – 10s	1 - ?

Design Standards

- The National Electric Code – installation standard
- UL – product standards
- IEEE – component standards
- SAE – Society for Automotive Engineers for Electric and Hybrid
- Global – IEC, etc.

UL Design Standards – a sampling

- UL/ULC 2271- Batteries for Use in Light Electric Vehicle (LEV) Applications
- UL 62817 – Photovoltaic Systems- Design Qualification of Solar Trackers (new)
- UL 248 – DC Fuses
- UL 489 & 508 – Investigations Re: DC Microgrids and PV systems
- UL 810B – DC Power Capacitors
- UL 1066 – Power Circuit Breakers up to 1000 V AC and 1500 V DC in Enclosures
- UL1699B – Photovoltaic (PV) DC Arc-Fault Circuit Protection (new)
- UL 2202 – DC Charging Equipment for Electric Vehicles
- UL 2251 – Standard for Plugs, Receptacles, and Couplers for Electric Vehicles
- UL 60900 – Live Working – Hand Tools for Use up to 1000 V AC and 1500 V DC
- UL62852 – Connectors for DC-Application in Photovoltaic Systems (new)
- ANSI/CAN/UL 5800 – Battery Fire Containment Products

UL Design Standards – Lithium Ion Batteries

- UL 1642 – Lithium Batteries
- UL 2056 – Outline of Investigation for Safety of Lithium-ion Power Banks
- UL 2580 – Batteries for Use in Electric Vehicles
- ANSI/CAN/UL – Standard for Unmanned Aircraft Systems

IEEE Battery Design Standards – not comprehensive

- IEEE WG 1679.1: IEEE Guide for the Characterization and Evaluation of Lithium-Based Batteries in Stationary Applications
- IEEE WG 1679.2: IEEE Guide for the Characterization and Evaluation of Sodium-Beta Batteries in Stationary Applications
- IEEE WG 1679.3: Draft Guide for the Characterization and Evaluation of Flow Batteries in Stationary Applications
- IEEE WG 1679.4: Guide for the characterization and evaluation of alkaline batteries in stationary applications
-
- P2962/D32: Draft Recommended Practice for Installation, Operation, Maintenance, Testing, and Replacement of Lithium-ion Batteries for Stationary Applications
- IEEE WG 3163: Recommended Practice for Sizing Lithium Batteries for Stationary Applications

IEEE PV and Energy Storage Design Standards – not comprehensive

- IEEE Std 1374-1998: IEEE Guide for Terrestrial Photovoltaic Power System Safety
- IEEE WG 1526: Recommended Practice for Testing the Performance of Stand-Alone Photovoltaic Systems

- IEEE Std 1491 -2012: IEEE Guide for Selection and Use of Battery Monitoring Equipment in Stationary Applications
- IEEE Std 1547.4 -2011: IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems
- IEEE Std 1657-2018: IEEE Recommended Practice for Personnel Qualifications for Installation and Maintenance of Stationary Batteries
- IEEE Std 1679 -2020: IEEE Recommended Practice for the Characterization and Evaluation of Energy Storage Technologies in Stationary Applications
- IEEE Std 3001.2-2017: IEEE Recommended Practice for Evaluating the Electrical Service Requirements of Industrial and Commercial Power Systems
- IEEE Std 946-2020: Recommended practices for the design of dc power systems for stationary applications
- IEEE WG 2993: Recommended Practices for Energy Storage System Design using Second-life Electric Vehicle Batteries
- IEEE WG 1375: Guide for the Protection of Stationary Battery Systems
- IEEE WG 2686: Recommended Practice for Battery Management Systems in Energy Storage Applications
- IEEE WG 2688: Recommended Practice for Energy Storage Management Systems in Energy Storage Applications

Electric Vehicle Design Standards

- SAE J2929_201302 – Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems Utilizing Lithium-Based Rechargeable Cells
- SAE J2288_202011 – Life Cycle Testing of Electric Vehicle Battery Modules
- SAE J1798/1_202008 - Recommended Practice for Performance Rating of Lead Acid and Nickel Metal Hydride Electric Vehicle Battery Modules
- SAE J2464_202108 - Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing
- SAE J2910_201404 – Recommended Practice for the Design and Test of Hybrid Electric and Electric Trucks and Buses for Electrical Safety
- SAE J1797_201608 – Recommended Practice for Packaging of Electric Vehicle Battery Modules
- SAE J1715_2022 – Hybrid Electric Vehicle (HEV) and Electric Vehicle (EV) Terminology

Summary of Design and **Worker Safety** Standards

Source of Code/Standard	Design to protect equipment/user/worker	Worker Safety Standard
UL	Many – 10s	0
NFPA	A few, 70, 855	1 – NFPA 70E -
IEEE	Many – 30+	2 – IEEE 1584, NESC (utility)
SAE	Some – 10s	1 - ?

Electric Vehicle Worker Safety Standards

- SAE J2344_202010 – Guidelines for Electric Vehicle Safety ?

Worker Safety Standards

- NFPA 70E – Standard for Electrical Safety in the Workplace
- IEEE
  - National Electrical Safety Code (NESC - utility)
  - 1584 –Guide to Performing Arc Flash Calculations

Proposal for revised/new worker safety Standards

Source of Code/Standard	Design to protect equipment/user/worker	Worker Safety Standard
UL	Many – 10s	0
NFPA	A few, 70, 855	1 – NFPA 70E - **revise**
IEEE	Many – 30+	2 – existing - IEEE 1584, NESC (a) New – risk assessment for special equipment (b) New – working on stationary Battery Banks (c) New – working on electric vehicles

(a) Study Group approved – PAR to submitted this summer, draft this fall – Lloyd Gordon
(b) BESS – soliciting members for study group – Dan Doan
(c) Electric vehicles - soliciting members for study group – Lloyd Gordon

Current Efforts on **DC Arc Flash Analysis**

NFPA 70E and/or IEEE

- All current DC arc flash models (with few exceptions) are:
  - Static – do not take into account dynamic arc behavior (e.g., electrode erosion or magnetic forces)
  - Linear – do not take into account time changing source or arc impedance
  - A mixture of empirical (based on data), circuit theory, and physics
- Current models being used for calculating incident energy for battery banks
  - Over estimate incident energy by a factor of 2 to 10,
  - such as Lee's method or the Maximum Power Transfer method.
- NFPA 70E Annex D.5, added in 2012, guide for DC incident energy analysis
  - Has three recommendations, based on limited data and models
  - Are all static and linear
  - Were meant to be a interim "place holder" until more work had performed
  - Are in need of updating

Future of DC Standards (as of Sept. 2023)

- Standards for DC Electrical Hazards are evolving
  - Thermal – some refinements for 2027 NFPA 70E
  - Shock – mature
  - Arc Flash – expect significant improvements in models
    - *Multiple test programs currently under way*
    - *Dynamic models taking into account arc behavior have been proposed*
    - *Nonlinear models taking into account nonlinear characteristics for various battery chemistries*
    - *A complete rewrite of Annex D.5 for 2027 NFPA 70E*

Future of DC Standards (as of Dec. 2023)

- *2027 NFPA 70E – Standard for Electrical Safety in the Workplace.*
  - *Article 320 – Batteries, update to include all battery chemistries, implement Risk Assessment*
  - *Article 340 – Power Electronics – add safe work practices for RF and subRF*
  - *NEW Article on Solar Power*
  - *NEW Article on Super Capacitors*
  - *DC Arc Flash – Complete rewrite – new methods, accounting for arc extinction*
- *IEEE*
  - *3 or more standards for Risk Assessment for DC, Battery Energy Storage, Electric Vehicles, etc.*

Summary

- Design standards and worker safety standards must work together to accomplish worker safety for Energized work on battery banks and solar power
- Models for DC Arc Flash Hazard Analysis for Battery Banks is under revision.
- Many proposed Public Inputs to NFPA 70E, due in early summer 2024 for 2027 standard)
- New articles for NFPA 70E, Chapter 3 – Special Equipment.
- Three proposed worker safety standards in IEEE

Premier International Workshop for Worker Electrical Safety


ESW 2024
2024 IEEE IAS Electrical Safety Workshop
March 4-8, 2024
El Conquistador Hotel • Tucson, AZ
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