ECE 398GG – ELECTRICAL VEHICLES

16. EV Deployment Issues

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ECE 398GG
Electric Vehicles

Lecture – EV Deployment Issues

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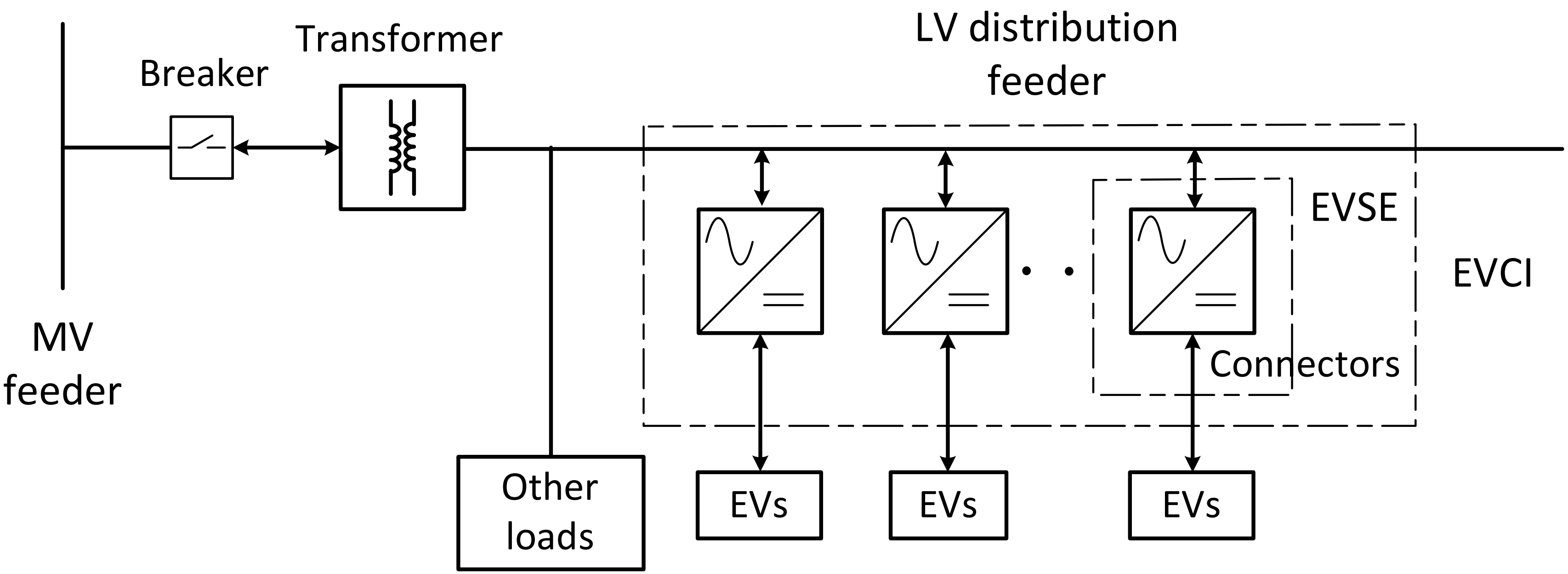
Outline

- EVs and elements of an EV charging infrastructure (EVCI) – enabling wider adoption of EVs
- EV charging requirements and options
- Opportunities for an EVCI – monetizing grid services
- Grid impacts – mitigation
- Extension/scalability to larger transportation infrastructure – example of a bus depot charging installation
- Fast charging stations
- Standards

Electrical power system and EV charging



- EV – electric vehicle, all electric transportation systems
- EVSE – electric vehicle supply equipment
- EVCI – electric vehicle charging infrastructure

EV technologies

Currently available or in development

- Battery EV (BEV) – the majority of recent offerings
- Plug-in hybrid (PHEV) – limited range EV
- Hybrid EV (HEV) – power train driven by battery and engine
- Fuel-cell EV (FCEV) – in development, may require battery and/or super-capacitor to meet acceleration requirements

Recent and expected developments

- All electric vehicles (green transportation) – battery EV with batteries meeting range requirements

EV vs internal combustion engine vehicle

- Charging times
  - On-board – with highest power now tested (350 kW EVs charged at least 5 times slower than liquid fuel refueling)
- Stored energy – limitations
  - on-board electrochemical batteries, less energy density vs liquid fuels
  - heavier vehicle and lower endurance range for each refueling stop-over
- Performance and efficiency – electric power train
  - Higher efficiency, mechanical reliability (fewer moving parts)
  - Possibility of using the brakes for energy recovery
- Operational costs
  - Lower if electricity costs are competitive
- Environmental benefits
  - No direct CO2 emissions, smaller impact over the complete life cycle

Electric transportation systems – features

- Electric transportation systems (EV) – large spectrum
  - Wheeled – people, bus, truck (heavy duty)
  - On and off road – mining, agriculture, warehouse
  - Other – electric aircraft, marine, rail
- Electric vehicles (EV) charging options
  - Chargers – for charging only – can be grouped in charging stations
  - Individual vehicle to grid (V2G) option – grid support provision
  - Individual vehicle to anything (V2X) – feeding diverse systems
- Constraints associated with electrification of transportation
  - Feasibility of displacing some or all fossil fuel supplied EVs
  - Availability of electric power to achieve 40 %, 100 % electrification – need for new electric power infrastructure

Charging options – passenger cars & others

- Home – Level 1 – ac – 1.5 kW, 120 V, 15 A – 8 km/h-charging
- Home – Level 2 – ac – 6.6-7.2 kW, 208/240 V, 30/40 A – 30-40 km-travel/hr-charging
- Commercial, workplace, public places – dc – Level 3 – 480 V, 3-phase, 400 A, 330 kW
- DC fast charger – 25-350 kW+, 3-phase – 200-250 km/h
- Other – ultra-fast, tailored charging
- Special applications – very large transportation systems in applications including
  - Rail transportation – locomotives
  - Marine transportation – ferries, passenger, freight ships; loading
  - Mining exploitation – trucks, loaders

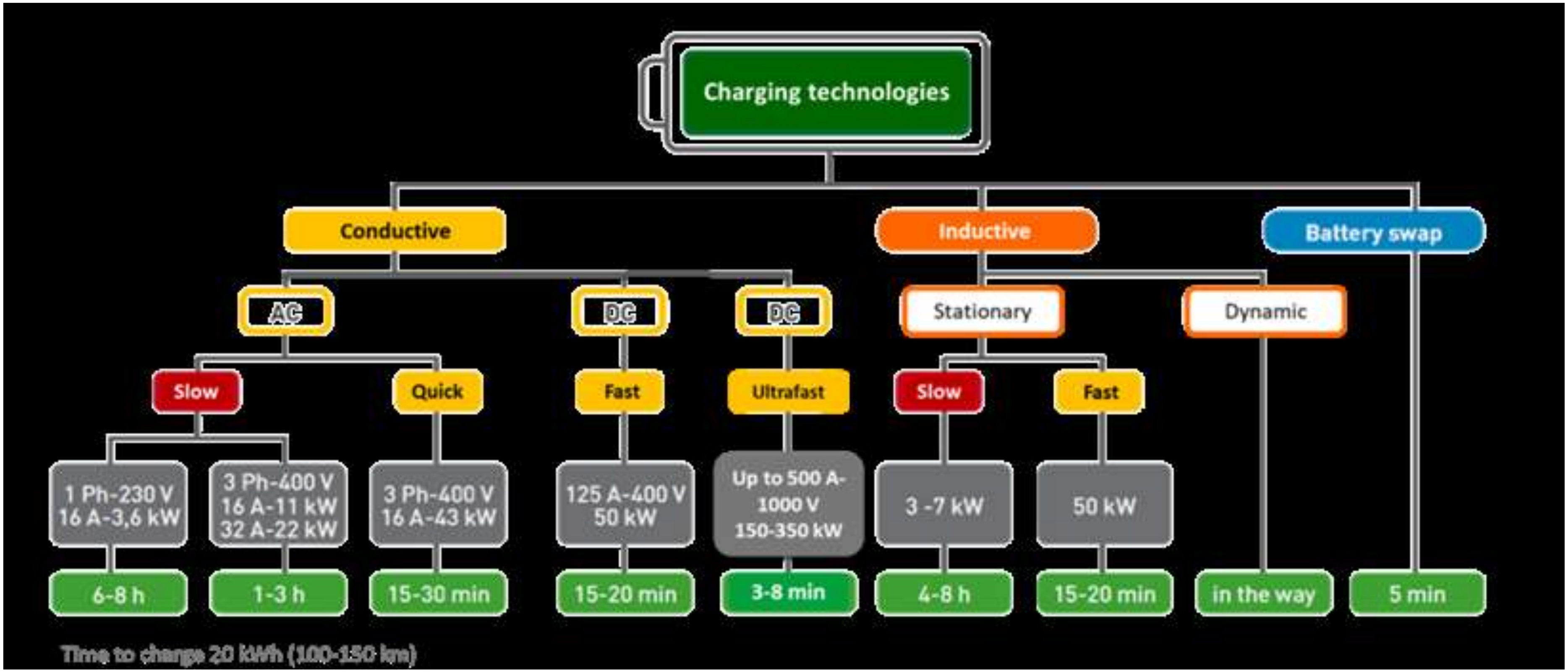
Electric grid EV loading

- Low voltage distribution (LV) – 120/240 V, 1-phase, 200-400 A
  - Home – Level 1 – ac – 1.5 kW, 120 V, 15 A – charging rate: 8 km/h
  - Home – Level 2 – ac – 6.6-7.2 kW, 208/240 V, 30/40 A – rate x 5
  - Level 2 chargers x 2 – increase in feeder loading of 40 %
- LV commercial distribution – 480 V, 3-phase, 400 A
  - Commercial, public places – dc – Level 3 – 170 kW/charger
  - Level 3 chargers – one feeder accommodates 2 chargers
  - Individual vehicle to grid (V2G) and to anything (V2X)
- MV distribution – 25 kV, 10-20 MVA feeders
  - Fast charging stations, 10 MW – 200 kW (car) / 1000 kW (truck)
  - DC fast chargers – station charges 50 (car) / 20 trucks at a time

CAT 793 BEV mining truck demonstration

7 MWh electric locomotive, 480VAC,500A

EV charging options/technologies



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Charging characteristics/parameters

Charging parameters				Battery capacity kWh
Rate	Voltage Vdc	Current A	Power kW	
Slow	400 or 800	60-400	50-150	50-250
Average	400 or 800	200-800	**150-400**	50-250
Fast	to 1500	300-1000	**200-1000**	100-500
Ultrafast	to 1500	800-3000	1000-4500	250-1000

Charging time/power calculations

- Assumption – a battery capacity of 250 kWh, charged to 80 % capacity (200 kWh), and zero conversion losses
- Charging times
  - Slow charging, at 400 V, 60 A, 24 kW: 8.3 hrs
  - Average charging, at 400 V, 200 A, 80 kW: 2.5 hrs
  - Fast charging, at 800 V, 300 A, 240 kW: 50 min
  - Ultrafast charging, at 1500 V, 800 A, 1.2 MW: 10 min
- Currently available EV battery size
  - Car – avg : 50 kWh – Tesla: 100 kWh – Large: 220 kWh (pick-up)
  - Bus: 350 kWh – Truck: 750 kWh (560 km), up to 800 kWh

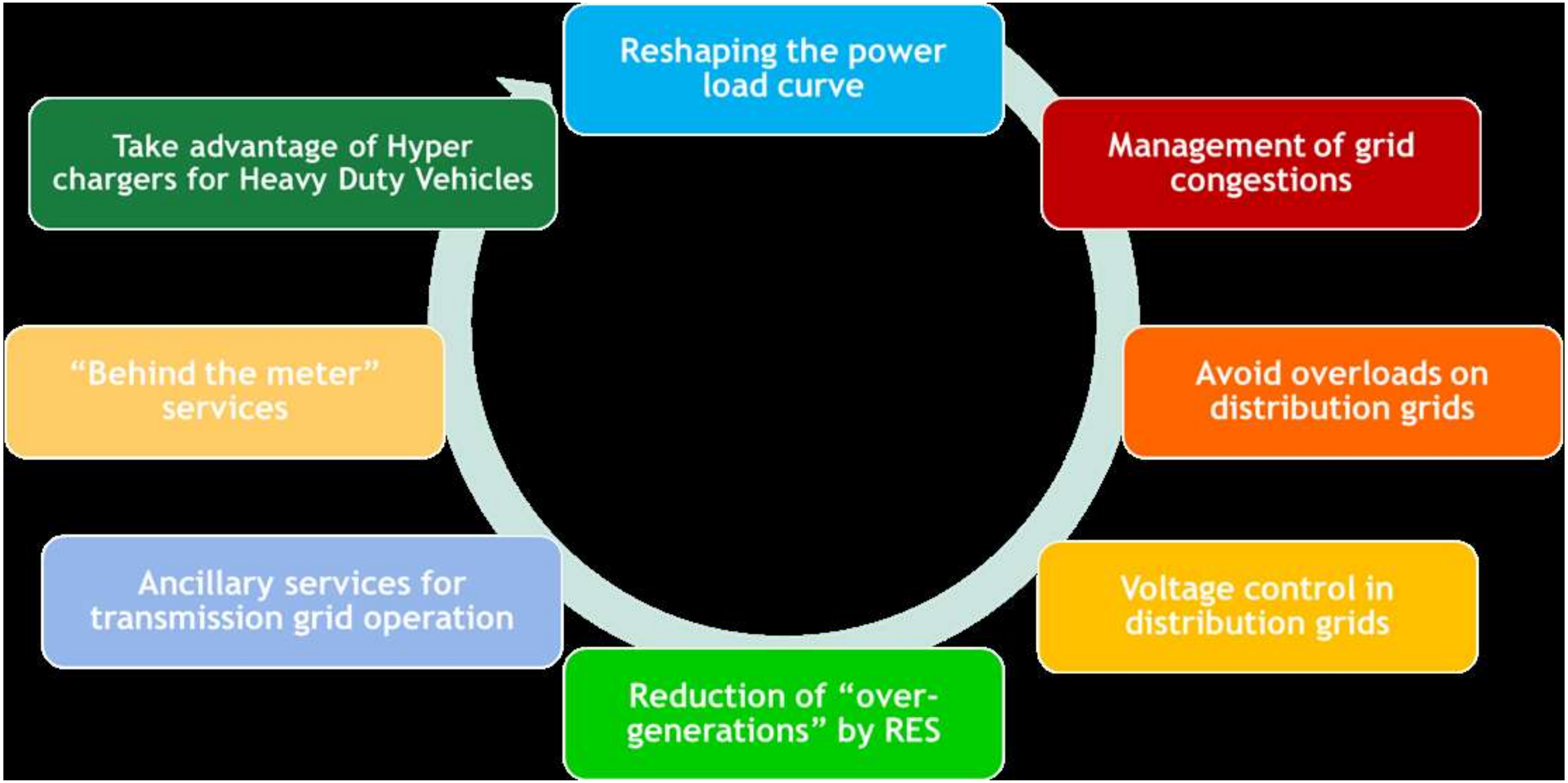
EVCI power requirements

- Assume an installation featuring multi-port MD/HD electric bus and MD/HD truck charging up to 1 MW
- Utility interconnection (transformer) with up to 2.5 MVA
- Assume 1 MW - 2.5 MW level, ignoring losses, simultaneous charging (largest today: 4.5 MW per connection)
  - 1 to 2.5 charging ports at 1 MW each – for fast charging
  - 2 to 5 charging ports at 500 kW each
  - 10 to 25 charging ports at 100 kW each
  - 50 to 125 charging ports at 20 kW each
- Charging time, for a 624 kWh battery, 90 min@375 kW
- Note: typical 25 kV distribution feeder, 3-phase, 10-20 MVA

EVCI deployment considerations

- Permitting and location
  - Real estate procurement – industrial sites, transportation hubs
  - Availability of the required power and energy at the location
- Securing funds for capital expenses – see also business case
  - Secured from the banks and/or other investors (venture)
  - Request for funding based on a business case (net revenues)
- Utility responsibilities – see also EVCI deployment options
  - Making power/energy available at the location
  - Infrastructure, feeder, substation
- Making a profit from charging – see business model
- Acquisition of CO_2- free electricity
  - Self generation – local renewable (PV), other clean energy sources

Managed EV charging benefits/opportunities



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Requirements for a viable business model

- Elements of a viable business model for a non-essential service
  - A service that customers are willing to pay for
  - A service that can be provided over a length of time sufficient to amortize the cost of building the infrastructure
  - A service that makes a sufficient profit for the promoter to stay in business
- Elements that enhance the business case – multiple uses and services, including
  - Charging EVs – selling kWh as an energy service, at a cost that varies with the time of day and duration of the charging
  - Providing grid services to the grid operator
  - Providing services to a third party
- Individual chargers vs chargers regrouped in a charging station

Economic assessment of V2X solutions

- Applicable to individual chargers
- Operational and economic trade-offs for the user and the vehicle
  - cost of battery damage/degradation
  - charging installation cost, infrastructure for bidirectional power (V2G) cost for electronics to enable V2G
- Options
  - slow/medium power charging, lower cost alternatives
  - optimizing the cost of on-vehicle and infrastructure electronics
- Trade-offs, under different EV penetration scenarios
  - optimal balance between the vehicle and infrastructure costs,
  - location, topology of chargers, interoperability, efficiency of V2X
  - centralized and decentralized management and control

EVCI functions – monetizing grid services

- Additional uses of the EVCI – multiple revenue sources, improving business case – see business model
- Services managed by an aggregator of EV chargers
- Grid services – power – marketable
  - Capacity, kW, including load peak shaving and shifting
  - Energy, kWh, including supplementing central power generation
  - Frequency support – regulation and short-term support
- Ancillary grid services – reactive power – value to be determined
  - Voltage support – regulation
  - Black start
  - Resilience and reliability

Types and uses of grid services

- Additional elements in the EVCI business case
- Grid services – utility perspective
  - Requested by the grid operator to meet operational requirements
  - Monetary value determined by the difference in cost to the grid operator of setting up their own services vs procuring the services from a third party (on the electricity market)
- Features and constraints – producer and user (utility)
  - Power and energy – associated with an energy and production cost – fossil fuels vs renewables (no energy cost)
  - Reactive power – no energy cost – locational
  - Black start, key to resilience – opportunistic, locational, operation dependent on infrastructure configuration

EV charging – potential grid impact

- Needed – public and workplace chargers increase 27% annually, 500,000 public chargers by around 2027
- Preparing for the future, avoiding potential failures/blackouts
- Challenge – ensure bulk power system (BPS) reliability, resilience, and security with EV loads – NERC responsibility
  - North American Electric Reliability Corporation
- Specific concern – EV charging behavior during infrequent grid disturbances that originate from the BPS
- Risk – Effects of unmanaged charging of EV charger power electronics on grid dynamics – risks of blackouts
- Solution – Developing grid-friendly EV charging dynamic behavior

EV charging – mitigating negative impacts

- Power system stability concepts – transient stability, frequency stability, voltage stability, ride-through performance, and essential BPS reliability services required to manage them
- Recommendations on mitigating negative impacts on grid reliability of EV chargers – specific aspects – summary
- Steady-state consumption control – constant I vs constant P
- Power factor – constant at 0.985 (lead or lag)
- Frequency response – power vs frequency control – 5 % droop
- Frequency response – rapid P reduction for large f excursions
- Ride-through f and V performance – remain connected during grid disturbances

Monetization of grid services – revenues

- Challenges – ability to assess the utility needs for grid services and to sign a contract with the utility at a price that allows the EVCI operator to provide the services (covering capital, CapEx, and operational OpEx costs)
- Currently marketable services – value can be established
  - Electric power and energy – location injection gnostic
  - Short term power injection – demand curtailment for frequency support
- Limited impact/use services – value more difficult to establish
  - Reactive power – voltage support – locational injection/impact
  - Resilience and reliability – need to define terms and expectations
  - Black start – limited use after blackout – location and availability

EV charging infrastructure options/size

- Urban – slow chargers – ac charging – LV grid
  - Public, home, company fleets
- Public – high power fast chargers – dc charging – MV grid
  - Fast chargers (50 -150 kW) – fuel stations
  - Urban super hubs (150 – 350 kW) – dedicated areas
- Bus/truck depots – ac or dc charging – MV grid
  - High numbers (10-100), night charging
- Highway hyper hubs – dc charging – MV/HV grid
  - Hyper fast chargers (150 – 350 kW)
- Special applications – dedicated charging stations for marine, mining, aircraft, warehouse applications

EVCI types and features – public space

Installation type	Grid impact analysis			
	Power	**Energy**	**Reinforcement**	**Flexibility / grid services**
Public slow chargers	Power flows and hosting capacity Voltage profile/regulation Peak shaving possibly needed	Limited impact. Adds to distribution loads	May require transformers and feeder upgrade	High (long EV connection times)
Urban chargers and hyper hub	Same as for slow chargers May result in signifcant increase in power on MV lines May require upgrade in MV lines and/or substation equipment May require local battery energy storage	Increase in energy requirements May require peak load management	Dedicated feeders and substation may be required Transformer replacement	Limited Can be enhanced by aggregate control in combination with battery energy storage These additions allow participation in grid services

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EVCI types and features – charging stations

Installation type	Grid impact analysis			
	Power	**Energy**	**Reinforcement**	**Flexibility / grid services**
Bus depot	Requires dedicated feeder/infrastruture and coordination with grid and transprtation system operators	Managed as other large industrial installations	Dedicated feeders and substation may be required	Full control over predictable charging requirements allows provision of grid services Subject to transportation system constraints
Highway hyper hub	May result in large short term demand Requires dedicated feeder/infrastruture and coordination with grid operator in appropriate location	Managed as large industrial installations May require local energy management and storage	Dedicated feeders and substation required	Potential for the provision of grid services may be limited by priority given to EV charging Flexibility enhanced by local storage and generation (microgrid)

EVCI deployment – illustrative example

- Bus depot example
- Constraints – large amounts of power required
  - Bus depot power requirements: 6.5 MW
- Connection to the electric power system
  - Bus depot connection: medium voltage (MV) distribution feeder, 25 kV
  - Typical feeder power: 20 MVA, 10 MW
- Location – real estate requirements
  - Bus depot example: large PV solar arrays, corresponding to bus parking lot
  - Conventional generation: much smaller footprint
- *Note – the EV infrastructure should be compared to existing gas/diesel stations*

EVCI example – electric bus depot

- Context – Bus depot, Maryland, deployed by a transit operator, a energy service provider and an equipment manufacturer
- Project – resilient sustainable transportation with *energy as a service* microgrids
- Managed as a microgrid, a self contained distribution grid; may be islanded (planned or unplanned islanding, from the utility perspective)
- Multiple goals, economic, environmental (emission reduction) and energy supply security (ensuring resilience)
  - Convert 70 diesel buses to electric power
  - Power the fleet using a smart microgrid, to help the county boost resilience and achieve net zero carbon emissions by 2035

EVCI assets – charging/generation

- Implementation – microgrid concept
- Microgrid – 6.5 MW microgrid, with
  - Generation: 3 x 633 kW generators
  - On-site solar PV: 1.6 MW, roof of the bus depot
  - Battery energy storage (BESS): 3 MW for balancing and back up
  - Local loads – may be curtailable (HVAC, other)
- Charging station – 4.14 MW charging capacity, charging bays
  - EV chargers: 18 x 180 kW, 3-dispenser chargers, for a total of 54 charging slots (cables)
  - EV chargers: 2 x 450 kW, pantograph type (for overhead wire connection) rapid chargers

Charging station layout – bus depot

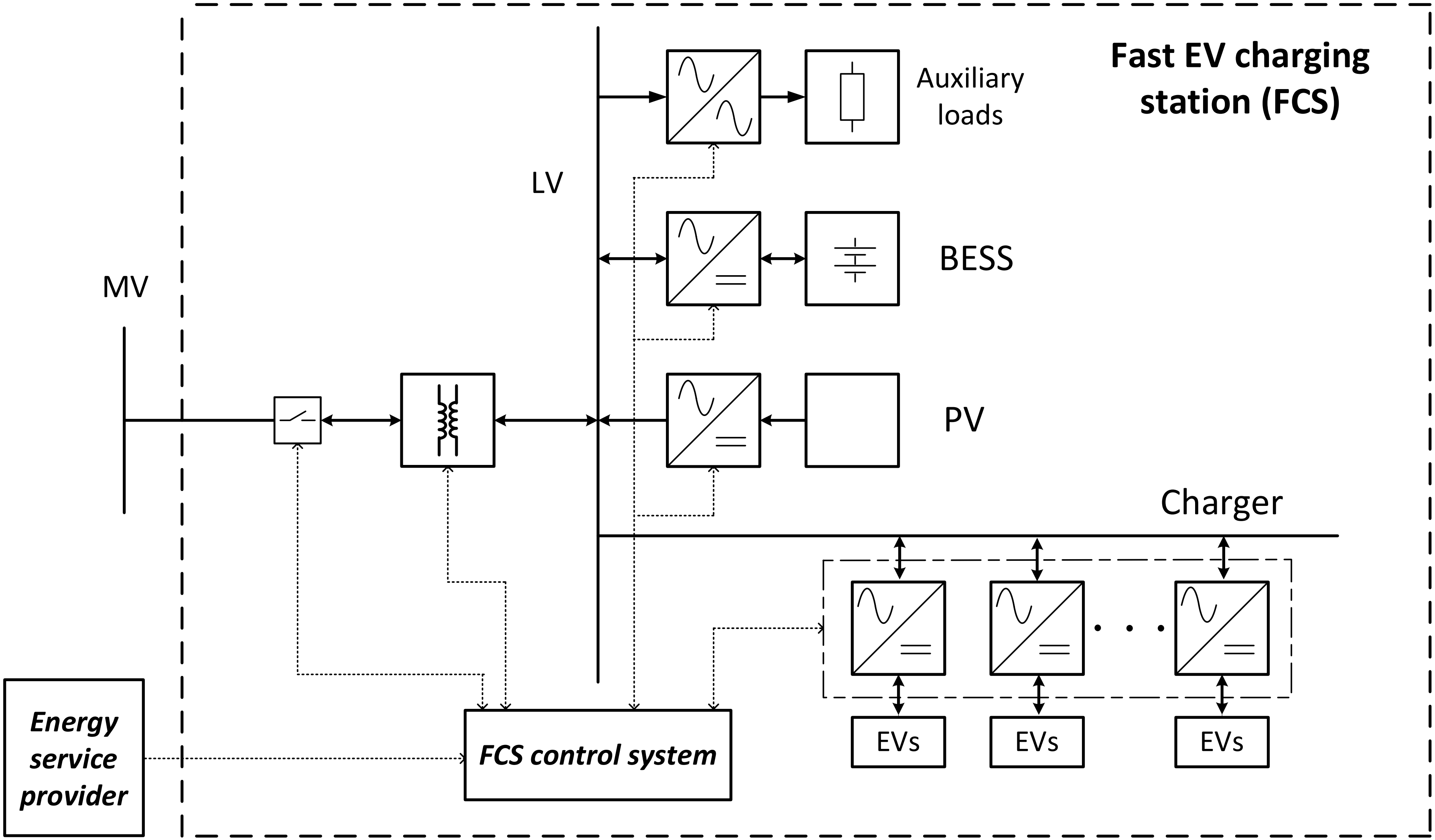
EVCI Germany – charging station

- Bus depot Hamburg (ABB)
- Implementation – 44 x 150 kW chargers – 6.6 MW peak
- Overhead wire and pantograph
- Mezzanine mounted chargers
- EV charging value chain (ABB) – evolution – business case
  - Starting from passenger car, to bus, to truck chargers
  - Add battery energy storage system – peak shaving
  - Add renewable energy resources – solar and wind
  - Add building management systems
  - Add a site energy optimization
  - Expand into energy trading – bidirectional power flow (V2G)

Business model – bus depot example

- Technical benefits of a third-party charge management
- Business case dependent on the local electricity prices
- Energy service provider (ESP) or service provider
  - Finances, designs, builds, owns, operates and maintains the microgrid assets, including generation, storage and chargers
  - Sells energy to the bus depot operators, using an *energy and a service* model
- Model – private sector provides capital and expertise in design, operation and maintenance of the charging infrastructure; benefits
  - Alleviating budget concerns
  - De-risking long-term operations, cost predictability

Fast charging station microgrid – structure



EVCI/FCS control aspects

- Decentralized energy solution – microgrid assets include
  - On-site renewable generation coupled with
  - Battery energy storage (BESS)
  - Dispatchable generation (diesel/gas engine driven generators), or combined heat and power generator (CHP), as required
  - Alternate fuel generation - hydrogen
- Dynamic control – functions include
  - Forecasting – generation from renewables, load
  - Generation and consumption matching/optimization
  - Managed charging
  - Emission reduction strategies and climate adaptation (resilience)

EVCI/FCS control system functions

Distribution grid

Fast charging station control system

Level	Functions	
Level 3	Higher level functions – ADMS/DERMS, service provider	
	Operator interface	Communications/SCADA
	Electricity market/pricing	
Level 2	Core level functions – Charging station / POI level	
	Charging requirements	Energy estimation/scheduling
	Charging profiles/optimization	Interconnection/grid interaction
Level 1	Lower level functions – EV chargers / DER / devices	
	Real/reactive power control	Device specific functions
	Voltage control	

Assets, devices and components

EVCI/microgrid structure – benefits

- Sustainable energy supply – integrating RES
- Reliability – requires redundancy and energy reserves
- Resilience – continued operation in case of power outages
  - operation possible independently of the grid
  - Possibility of reduced charging power, if the microgrid is partially fed from the grid under normal operation
- Notes: definition of reliability and resilience of the power grid
  - Reliability: Ability to balance supply and demand in real time by managing variability, ramping constraints, and flexible loads
  - Resilience: Ability to prepare for and adapt to changing operating conditions, and to withstand and recover rapidly from major disruptions caused by naturally occurring threats and other incidents

Fast charging station microgrid – benefits

- Fast charging stations (FCS) enable large scale transportation electrification through fast EV charging
- Exploiting/aggregating renewable energy resources (RES) for EV charging – reducing carbon footprint
- Possibility of net zero FCS operation using RES and BESS
- Supporting the electric grid by providing grid services
- Resilient/reliable operation of FCS through islanding
- Enabling FCS market participation (USA FERC 2222)
- Possibility of deploying interconnected FCS – energy exchange between a number of FCS

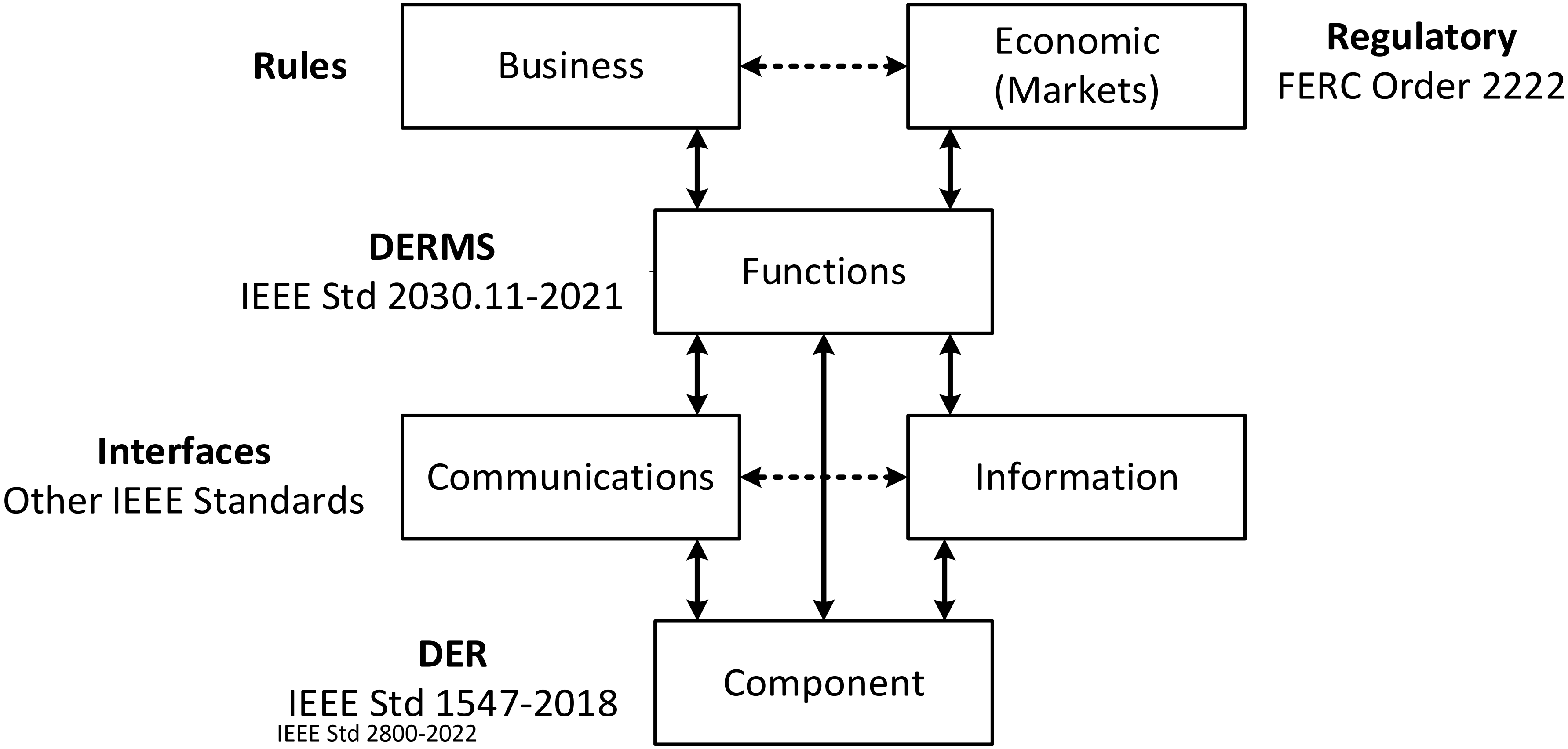
IEEE Standards Association (SA) – standards

- Types of standards
  - Standards – mandatory requirements – equipment *shall* meet…
  - Recommended practice – recommendation equipt *should* meet…
  - Guide – guidance on implementation – *permitted*, *able* to
- Context
  - Usually reflects current practice – example: machine parameters
  - Occasionally forward looking, addressing new issues
- Standard series of interest
  - Equipment – 1547, 1xxx, 2xxx
  - Systems – smart grid systems, inc microgrids, DERMS, FCS
- Justification and use of standards – provides support in
  - Drafting requests for proposal (RFP)
  - Understanding configuration and implementation of systems

IEEE DER/IBR and smart grid standards

- DER and fast charging station related standards and guides
- Published
  - IEEE Std 1547-2018 – Distributed energy resources (DER) grid interconnection standard – distribution
  - IEEE Std 2800-2022 – Inverter based resources (IBR) interconnection – transmission
  - IEEE Std 2030 – Smart grid interoperability guide – model
  - IEEE Std 2030.7/8 - 2017 – Microgrid controller functional specification / testing
  - IEEE Std 2030.11-2021 – DER management systems (DERMS) functional specification
- Under development
  - IEEE P2030.4 – interoperability guidelines
  - IEEE P2030.13 – fast charging station functional specifications

FCS interoperability in smart grids



Source: Adapted from the Smart Grid Interoperability Model (SGRIM) in IEEE Std 2030™-2011