Optimal Sensor Placement for Fault Diagnosis and Isolation in Aerospace Battery Packs

2020 NASA AEROSPACE BATTERY WORKSHOP

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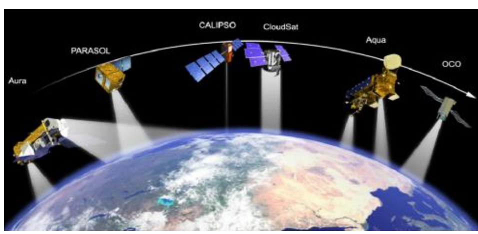
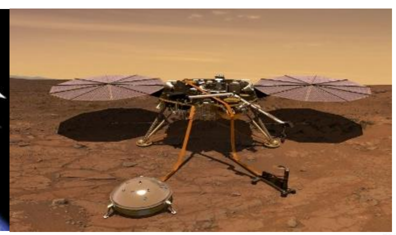
Outline

1. Motivation
2. Intrinsic properties of SP and PS battery pack configurations
3. Methodology description and single cell example
4. Analysis of traditional sensor set
5. Performing sensor placement to find minimal sensor set that can achieve complete fault isolation
6. Conclusions

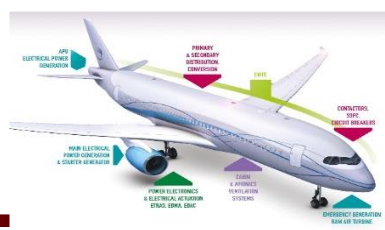


Satellites



Moon/Mars exploration

Launch vehicles



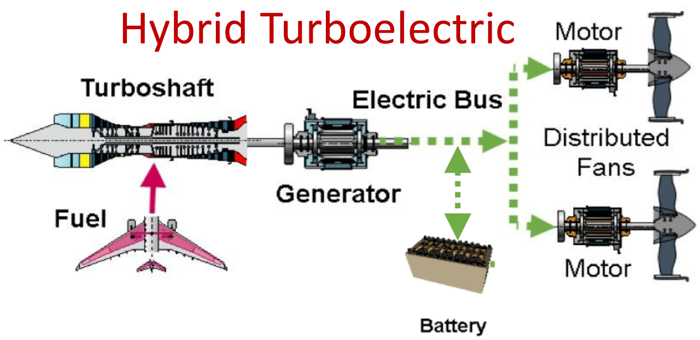
More Electric Aircraft

Electric/Hybrid commercial aviation

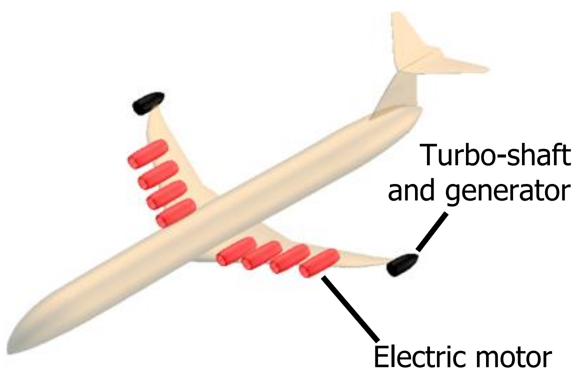
UAV/UAM

MOTIVATION

NASA ULI Electric Propulsion: Challenges and Opportunities



Felder, J.L., NASA Electric Propulsion System Studies, Report No. GRC-E-DAA-TN28410, 2015, Available at www.nasa.gov.



Distributed electric propulsion is a leading architecture for measurable CO_2 reduction on large commercial aircraft - regional, single aisle, and twin aisle.

- Two turbo-generators to supply electrical power to distributed motors
- Eight motors with embedded power electronics
- Integrated thermal management system
- Battery energy management can be charge-depleting or charge-sustaining; battery thermal management system is separate from powertrain

Challenge 1 System Integration

Success Criteria: Vehicle energy and CO_2 >20% improvement over existing solutions

Challenge 2 Ultra-High Power Density Electric Machine and Power Electronics

Success Criteria: Electric machines > 14 kW/kg, power electronics > 25 kW/kg, efficiency > 99%, bus voltage up to 2kV without partial discharge

Challenge 3 Energy Storage

Success Criteria: Power density and reliability (desired 450 Wh/kg)

Challenge 4 Advanced Control of Onboard Electrical Power Systems

Success Criteria: System remains stable at 20% voltage sag and 200% step load change

Challenge 5 Research Infrastructure for More Electric Aircrafts

Success Criteria: Sub-system and component prototyping and testing at elevation – 2 kV, 1 MW, 20 kRPM drive tests

Research on thermal management system design is integrated in every aspect of the project.

Perullo, C., Alahmad, A., Wen, J., D'Arpino, M., Canova, M., Mavris, D. N., & Benzakein, M. J. (2019). Sizing and Performance Analysis of a Turbo-Hybrid-Electric Regional Jet for the NASA ULI Program. In *AIAA Propulsion and Energy 2019 Forum* (p. 4490).

NASA ULI Electric Propulsion: Challenges and Opportunities

Design of a 2MWh battery pack for the 600nmi. 30% climb – 20% cruise mission profile.

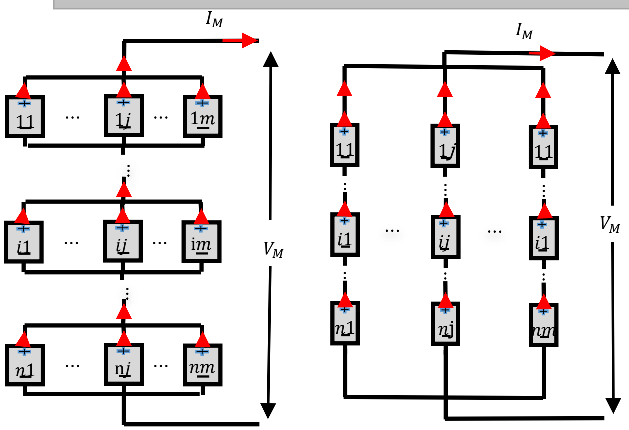
Cell	Cell 1	Cell 2	Cell 6	Cell 7	Cell 8	Cell 9
Format	18650 Cylindrical		Pouch			
Chemistry	LMO	NMC	NMC	Li-Si	Li-Metal	Li-S
Capacity assessment [Ah] (@1C, 23°C)	3.25	2.85	10.87	10.24	(19.40)	(14.7)
Energy Density assessment [Wh/kg] (@1C, 23°C)	237	215	224	336	(478)	(363)
Experimentally Tested?	Yes				No	No
ΔSoC_{avail}	(10-95)%					
$m_e n_e$ *- Total Cell Number*	**176,472 (516s x 342p)**	**196,560 (504s x 390p)**	**51,816 (508s x 102p)**	**54,752 (472s x 116p)**	**27,608 (476s x 58p)**	**66,990 (770s x 87p)**
Max C-rate (discharge)	2.20	2.26	2.16	2.15	2.28	2.06
Heat Generation (kW) (Peak/Average)	672 / 66	357 / 42	438 / 41	330 / 24	74 / 7	-
Efficiency [%] (Min/Average)	88 / 97	90 / 97	92 / 98	94 / 98	94 / 98	-
Pack Weight (Tons)	**8.39**	**9.26**	**8.88**	**5.91**	**4.16**	**5.69**

Sergent, A., Ramunno, M., D'Arpino, M., Canova, M., & Perullo, C. (2020). *Optimal Sizing and Control of Battery Energy Storage Systems for Hybrid Turboelectric Aircraft* (No. 2020-01-0050). SAE Technical Paper.

Definition of design optimization problem for large scale battery packs

Assumption: cell selection and pack sizing has already taken place (see presentation on Thursday 'A Comparative Study of Li-ion Battery Technologies for Hybrid-Electric Regional Aircraft Applications'

Basic Unit Design and Sizing

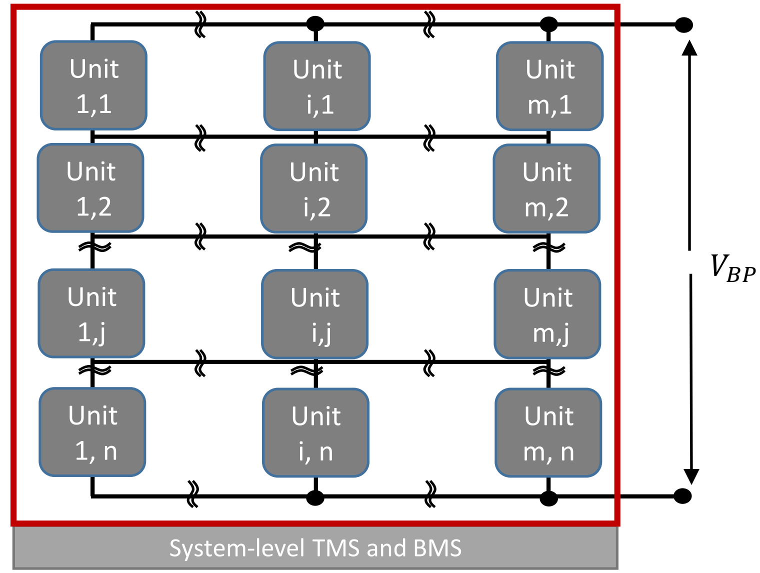


$nSmP$ $mPnS$

Design parameters

1. **Architecture** – SP vs. PS in different modular configurations.
2. Type, number and location of **sensors**
3. **Balancing** (if passive, answer is unique for each architecture, if active there are more options)
4. **Protection device** sizing and placement

Pack Design



Design parameters

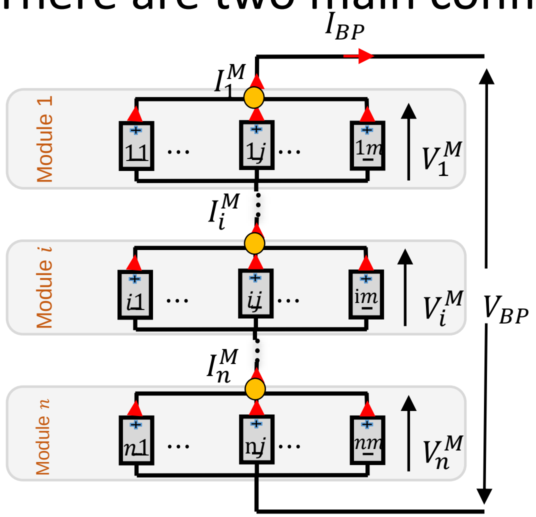
1. **Architecture** – SP, PS and combinations.
2. Type, number and location of **sensors**
3. **Protection device** sizing and placement

Design objectives: $ cost, Diagnostic capabilities, Reliability, Adaptability to component variation, ……

Battery pack configurations

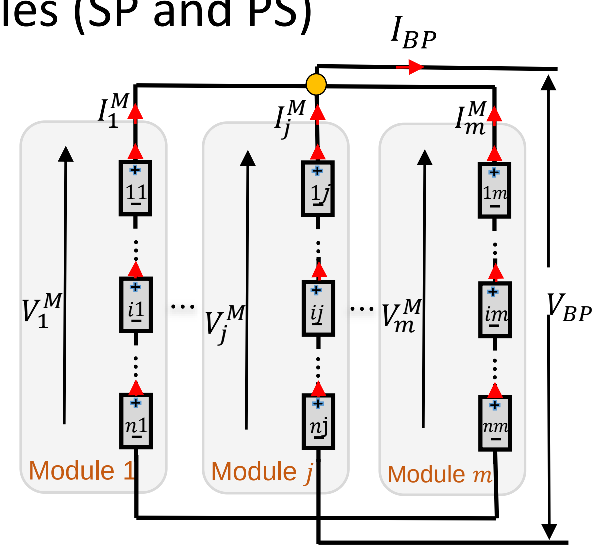
NASA ULI Hybrid turbo electric configuration require a large number of cells (10-100 of thousands of cells) interconnected together to access to the additional fuel burn reduction (up to 20% compared to turboelectric)

There are two main configurations for battery pack modules (SP and PS)



***n*S*m*P**
Series of parallel cells

***m*P*n*S**
Parallel of series connected cells



1. Explore the intrinsic properties of battery module architectures (SP and PS)
2. Effects of current and voltage unbalance considering
   1. Capacity and resistance unbalance
   2. Short circuit *(this will affect the sizing/selection of protective devices)*
3. Sensor requirements for faults detectability and isolabilily (traditional vs optimal) *(this will affect the selection of sensor set)*

Cai, Y., Cancian, M., D'Arpino, M., & Rizzoni, G. (2019, July). A generalized equivalent circuit model for large-scale battery packs with cell-to-cell variation. In *2019 IEEE National Aerospace and Electronics Conference (NAECON)* (pp. 24-30). IEEE.

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INTRINSIC PROPERTIES OF SP AND PS

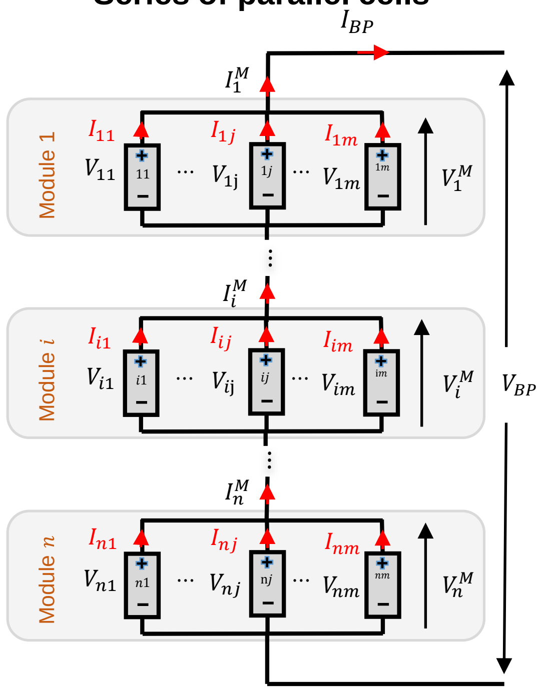
Battery modeling - Two architectures are commonly considered

Battery plant model consists of:
- **0^{th} order equivalent circuit models (ECMs)**
- **lumped-parameter thermal models**
- **The KCL/KVL.**

Battery cell model

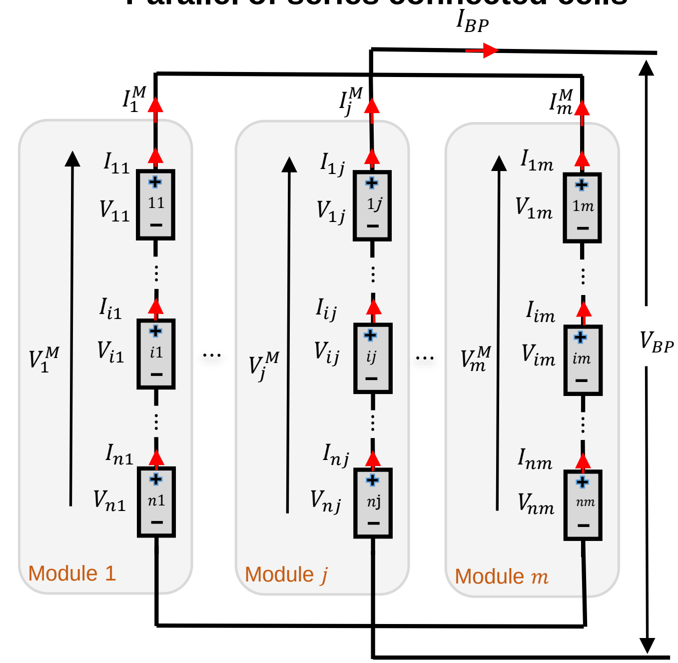
$$V_{ij} = V_{oc,ij} - R_{ij} I_{ij}$$
$$\frac{dSOC_{ij}}{dt} = -\frac{I_{ij}}{Q_{ij}}$$
$$V_{oc,ij} = f\,(SOC_{ij})$$
$$mc_p \frac{dT_{ij}}{dt} = R_{ij}(I_{ij})^2 - Q_{TMS}$$

$nSmP$
Series of parallel cells



Ideal conditions	$nSmP$	$mPnS$
# voltage sensors	n	$n \times m$
# current sensors	$n \times m$	m
# balancing circuits	n	$n \times m$
# fuses/ protections	$n \times m$	m

$mPnS$
Parallel of series connected cells



KCL & KVL for $nSmP$

$\sum_{j=1}^{m} I_{ij} = I_i^M = I_{BP} \qquad \forall i = 1 \cdots n$

$V_{i1} = \cdots = V_{ij} = \cdots = V_{im} = V_i^M \qquad \forall i = 1 \cdots n$

$\sum_{i=1}^{n} V_i^M = V_{BP}$

I^M = module current
V^M = module voltage

KCL & KVL for $mPnS$

$I_{ij} = I_j = I_j^M \qquad \sum_{j=1}^{m} I_j^M = I_{BP} \qquad \forall i = 1 \cdots n$

$\sum_{i=1}^{n} V_{i1} = \cdots = \sum_{i=1}^{n} V_{ij} = \cdots = \sum_{i=1}^{n} V_{im} = V_j^M = V_{BP} \qquad \forall j = 1 \cdots m$

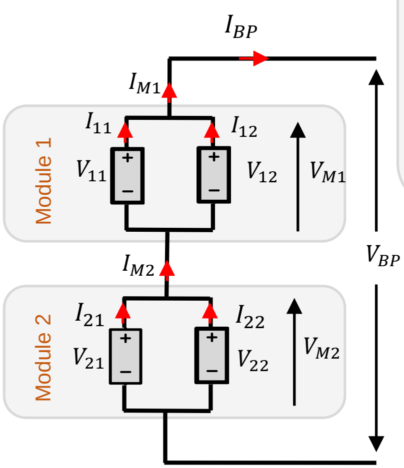
Battery Pack Architecture comparison using Bipartite Graph

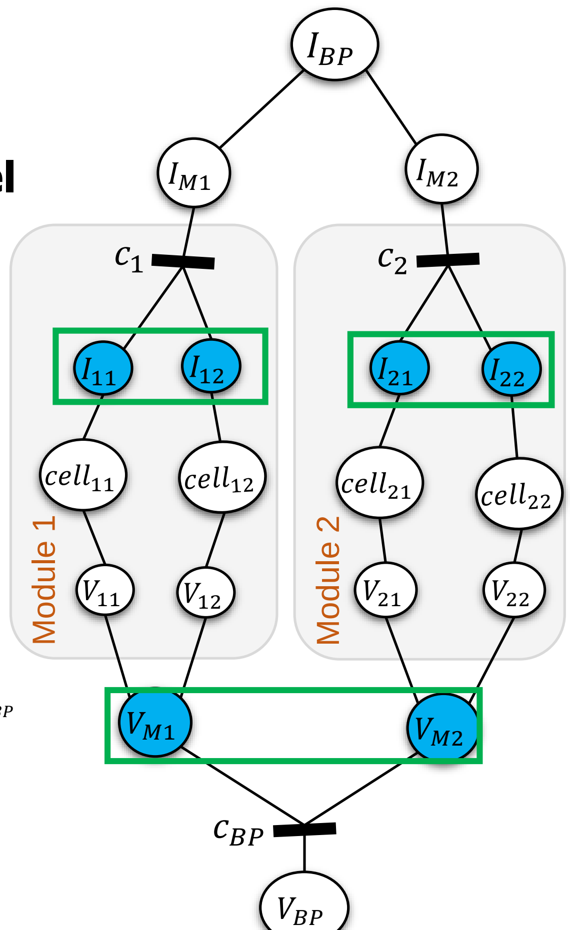
Bipartite Graph is a graphical representation of a model and it is used to analyze the connection between known variables, unknown variables, and faults.

- **Thin Line connects variable those are always equal.**
- **Think Line represents a sum (constraint). The sum is always true, but the element of the summation can be unbalanced due to parameters variation.**

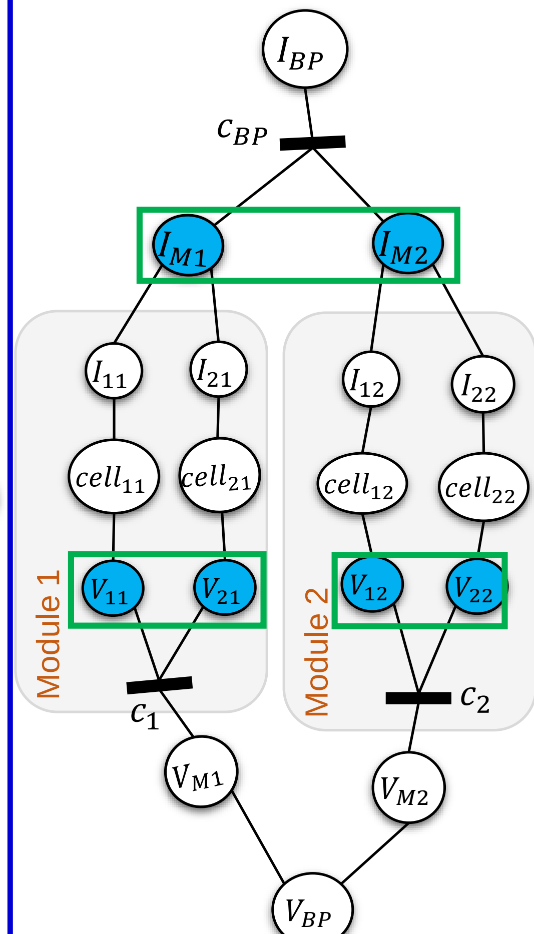
Variables in a green box are equal to each other in ideal case (if the cells are equals and have the same temperature).

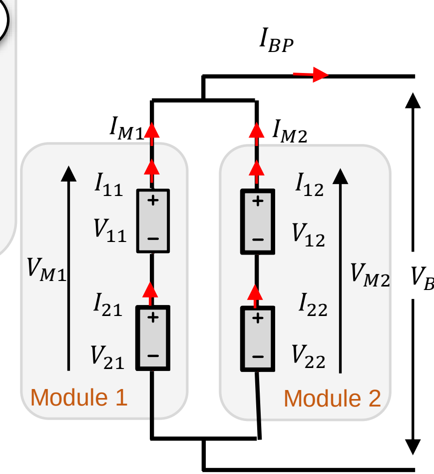
*n*S*m*P
Series of parallel cells





*m*P*n*S
Parallel of series connected cells





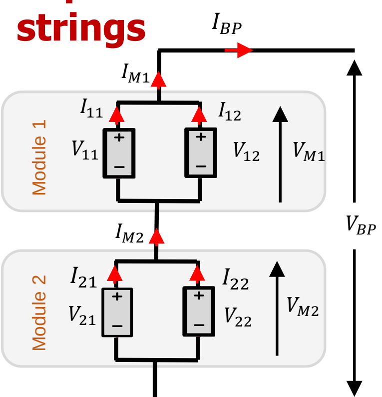
Battery Pack Architecture comparison using Bipartite Graph

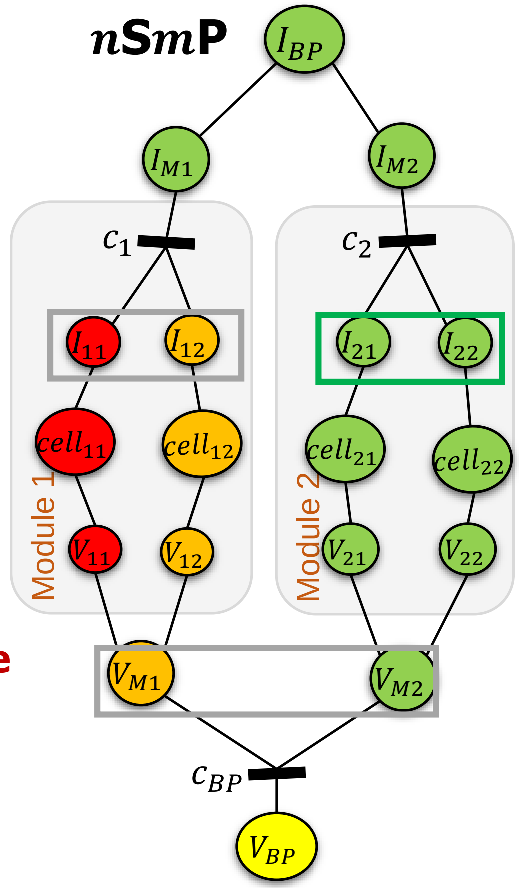
Module 1:
$cell_{11}$ has a problem $\rightarrow$
$I_{11} \neq I_{12}$ imbalance $\rightarrow$
$V_{M1} \neq V_{M2}$ unbalance

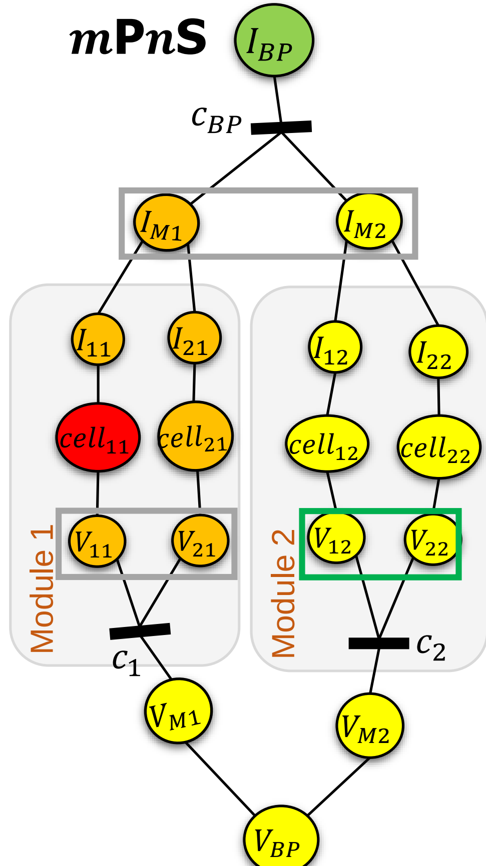
Module 2:
$I_{21} = I_{22}$ not affected.
V_{M2} is not affected.

Pack:
I_{BP} fixed (requirement)
$I_{M1}=I_{M2}$ not affected
V_{BP} affected

The fault of one cell is kept inside the module, however the entity of the current imbalance is high due to the limited impedance of the strings







A circle in red represents a cell with problem.

A circle in orange represents a variable is affected seriously.

A circle in yellow represents a variable is affected but not that seriously as in orange.

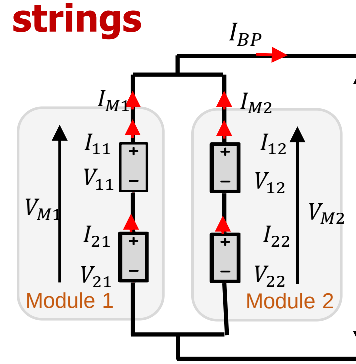
A circle in green represents a cell is not affected.

Pack:
I_{BP} fixed (requirement)
$I_{M1} \neq I_{M2}$ imbalance$\rightarrow$ $V_{M1} = V_{M2}$ affected$\rightarrow$ V_{BP} affected.

Module 1:
$cell_{11}$ has a problem$\rightarrow$
$I_{M1} = I_{11} = I_{21}$ is always true $\rightarrow$ $V_{11} \neq V_{21}$ imbalance $\rightarrow$ V_{M1} affected

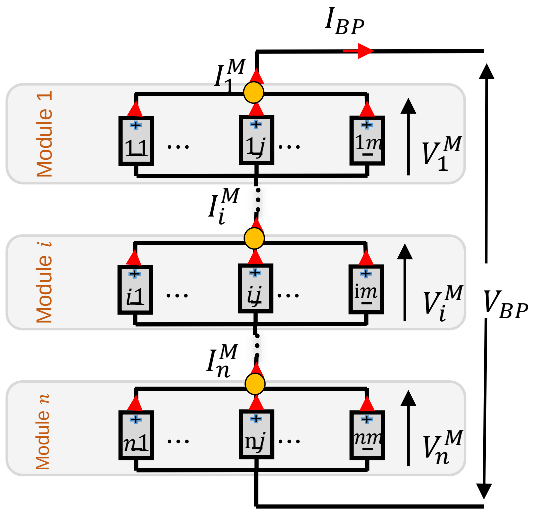
Module 2:
$I_{M2} = I_{12} = I_{22}$ is always true, but different current $\rightarrow$ $V_{12} = V_{22}$ affected $\rightarrow$ V_{M2} affected

The fault of a cell affect all the pack, however the entity of the current imbalance is lower due to the high impedance of the strings



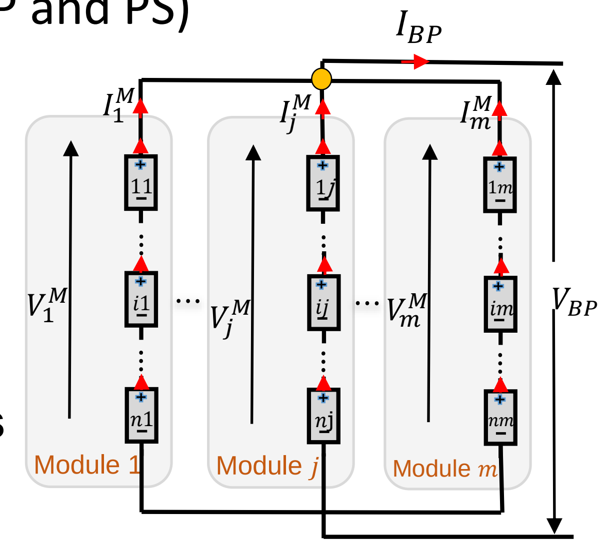
Two commonly used battery pack topologies

- There are two main configurations for battery packs (SP and PS)



***n*S*m*P**
Series of parallel cells

***m*P*n*S**
Parallel of series connected cells



Mostly used in automotive because of the reduced number of cell voltage sensors	**Considered by NASA for some space and aviation applications**
The fault or parameter unbalance of one cell is kept inside the module (positive), however the entity of the voltage/current imbalance is higher (negative)	The fault or parameter unbalance of a cell affects all the pack (negative), however the entity of the voltage/current imbalance is reduced (positive)

- *Which architecture will need less expensive sensor set to monitor cell condition?*
- *When there is an unhealthy cell, which architecture will need less sensors to detect and isolate the unhealthy cell?*

Use of Structural Analysis methods as sensor placement tool.

METHODOLOGY DESCRIPTION

Definition of Structural Analysis and example for single cell model

Analytical Model

Plant Equations: (a single cell)

e_1: $V_{11} = V_{oc11} - R_{11} I_{11}$

e_2: $\frac{dSoC_{11}}{dt} = -\frac{I_{11}}{Q}$

e_3: $V_{oc11} = f(SoC_{11})$

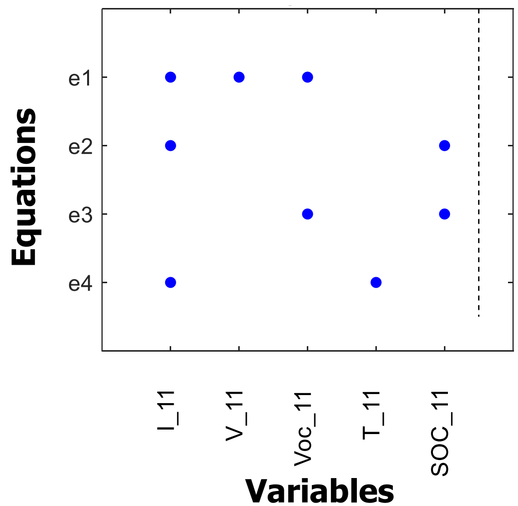
e_4: $mc_p \frac{dT_{11}}{dt} = R_{11}(I_{11})^2 - Q_{TMS_{11}}$

Structural Model

Equations	Unknown variables				
	I_{11}	V_{11}	V_{oc11}	T_{11}	SoC_{11}
e_1	1	1	1	0	0
e_2	1	0	0	0	1
e_3	0	0	1	0	1
e_4	1	0	0	1	0

Incidence Matrix

Incidence Matrix



- Structural analysis investigates the model constraint structure, i.e., the connections between known variables, unknown variables, and faults.
- The connections can be represented through **bipartite graphs** or **incidence matrices**.

Toolbox/MATLAB

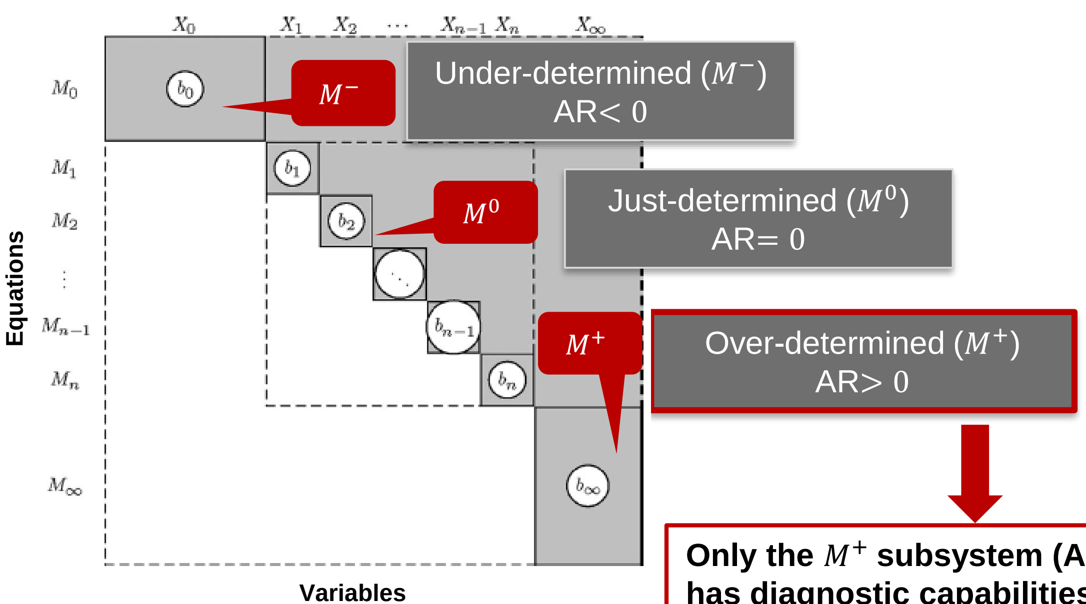
[1] Zhang, J., Yao, H., & Rizzoni, G. (2017). Fault diagnosis for electric drive systems of electrified vehicles based on structural analysis. *IEEE Transactions on Vehicular Technology*, *66*(2), 1027-1039.
[2] Rahman, B. M. (2019). *Sensor Placement for Diagnosis of Large-Scale, Complex Systems: Advancement of Structural Methods* (Doctoral dissertation, The Ohio State University).

Definition of Structural Analysis

Dulmage-Mendelsohn (DM)-Decomposition is used to evaluate the analytical redundancy (AR) of a structural model. The equations of the models are divided in classes:

- **Under-determined M^- (AR<0)** (e.g. I do not have enough eq.s to solve this part of the model, I need to transform some of the unknown variables in known variables by adding sensors)
- **Just-determined M^0 (AR=0)** (e.g. I do have just enough eq.s to solve this part of the model)
- **Over-determined M^+ (AR>0)** (e.g. I do have enough eq.s to solve this part of the model and I have some extra eq.s that I can use for diagnosis methodologies)

(Example)



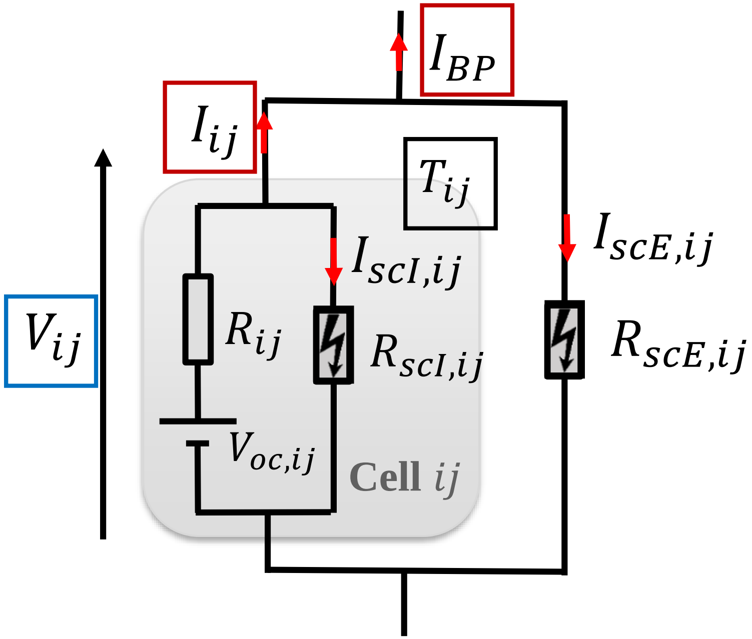
Only the M^+ subsystem (AR $>$ 0) has diagnostic capabilities.

Analytical redundancy (AR): The number of unknown variables minus the number of equations

Minimum structurally over-determined (MSO) set: An over-determined set of model equations such that its **AR= 1.**

Krysander, M., Åslund, J., & Nyberg, M. (2007). An efficient algorithm for finding minimal overconstrained subsystems for model-based diagnosis. *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans*, *38*(1), 197-206.

Definition of Structural Analysis – example single cell



possible sensor positions:
$\{I_{BP}, I_{11}, V_{11}, T_{11}\}$.

Plant equations with faults:

(a single cell is called $\boldsymbol{cell\ 11, i = 1, j = 1}$)

e_1: $V_{11} = V_{oc11} - R_{11}(I_{11} + I_{scI,11})$

e_2: $\frac{dSoC_{11}}{dt} = -\frac{I_{11}+I_{scI,11}}{Q}$

e_3: $V_{oc11} = f(SoC_{11})$

e_4: $mc_p \frac{dT_{11}}{dt} = R_{11}(I_{11} + I_{scI,11})^2 - Q_{TMS_1}$

e_5: $I_{scI,11} = \left(\frac{V_{11}}{R_{scI}}\right) f_{scI,11}$

e_6: $I_{scE,11} = \left(\frac{V_{11}}{R_{scE}}\right) f_{scE,11}$

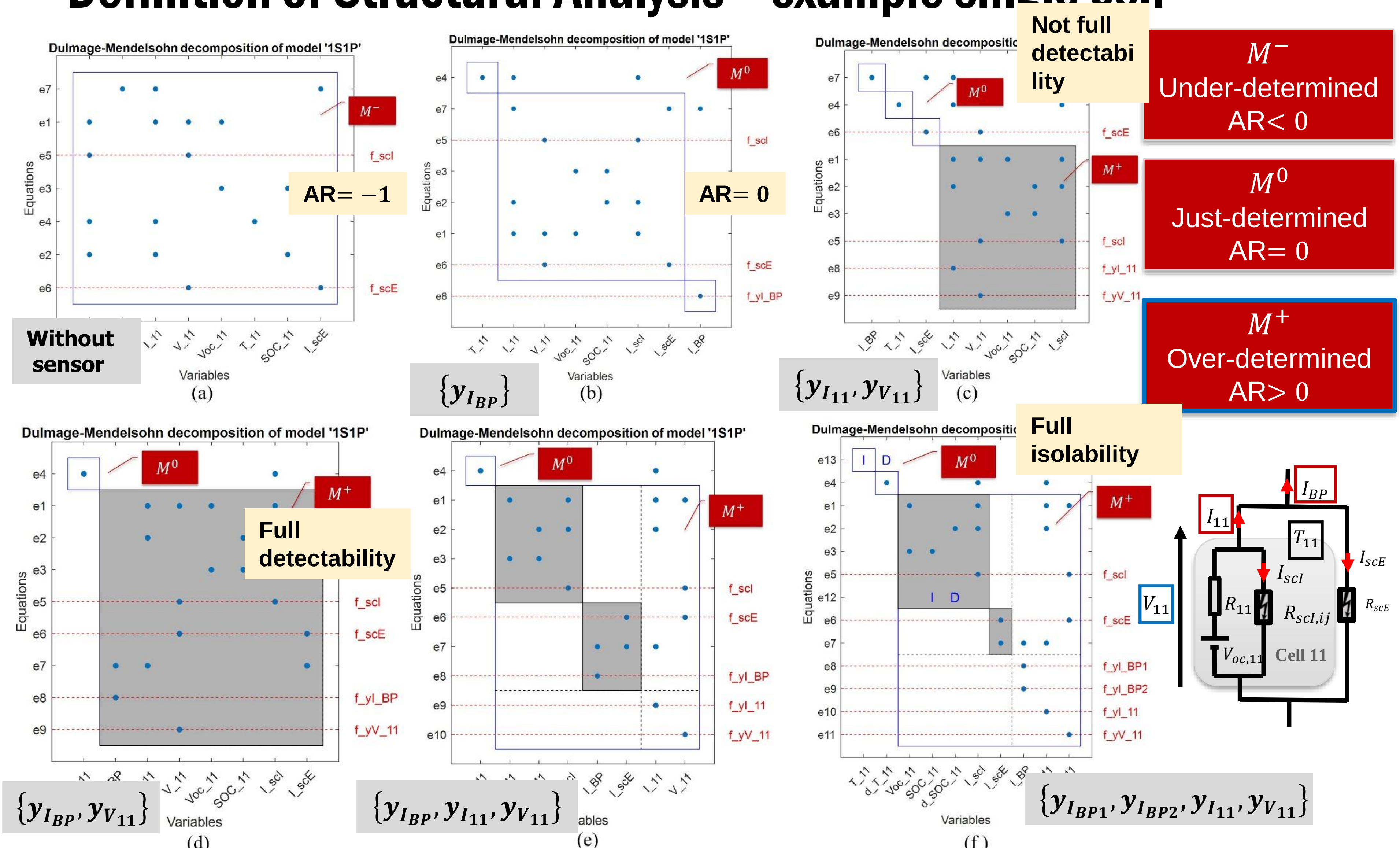
e_7: $I_{11} = I_{BP} + I_{scE,11}$

Sensor equation with faults:

$y_u = u + f_{y_u}$

The set of short circuit faults : $\{f_{scI,11}, f_{scE,11}\}$.
The set of sensor faults: depends on what sensors are added to the battery system.

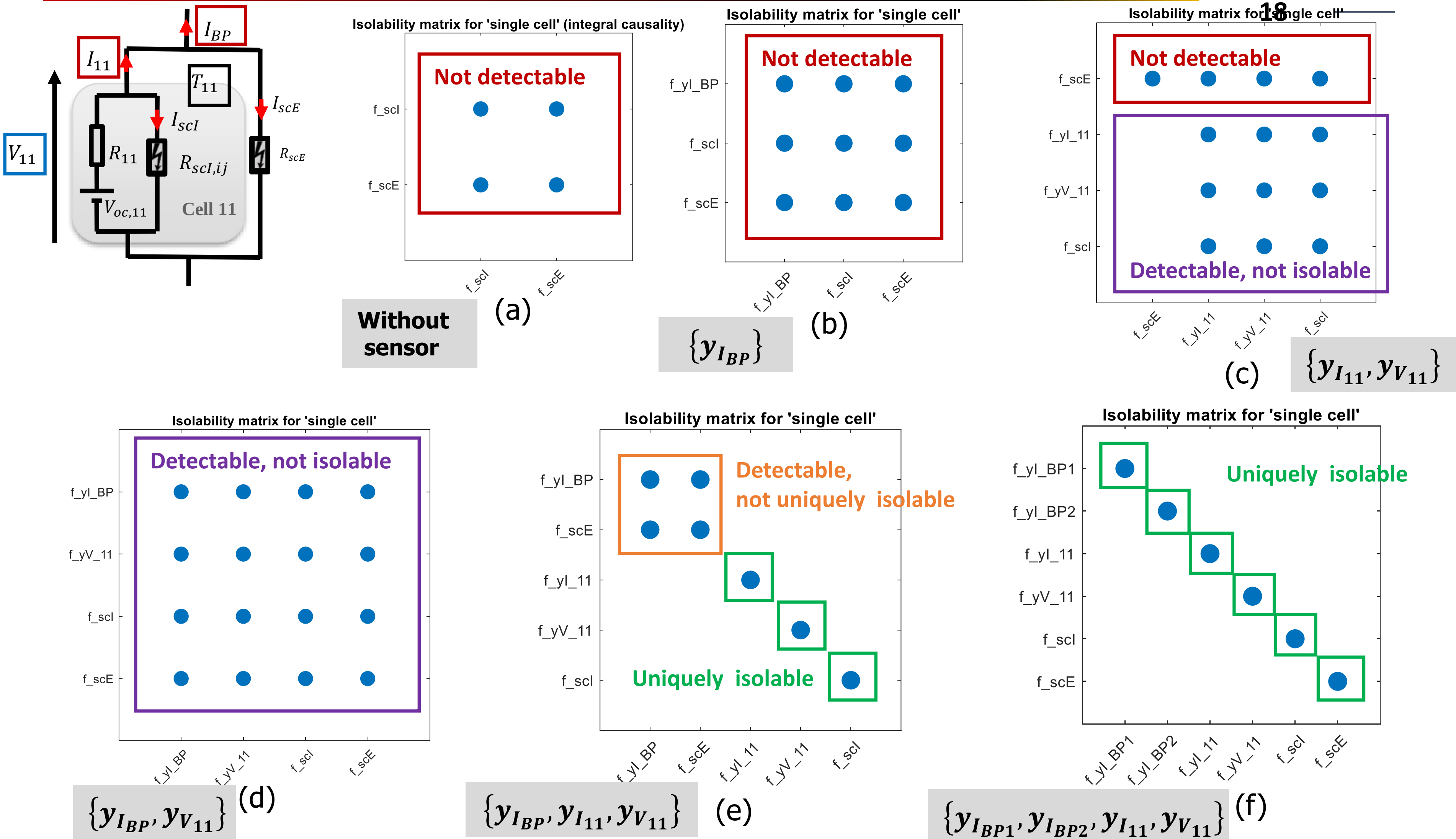
Definition of Structural Analysis – example single cell



If all the faults are included in the M+ (over-determined part of the model) but same equivalence class (gray area) -> all the faults can be detected, but not isolated

If all the faults are included in the M+ (over-determined part of the model) -> all the faults can be detected and uniquely isolated

Definition of Structural Analysis – example single cell



If all the faults are included in the M+ (over-determined part of the model) but same equivalence class (gray area) -> all the faults can be detected, but not isolated

If all the faults are included in the M+ (over-determined part of the model) -> all the faults can be detected and uniquely isolated

ANALYSIS OF TRADITIONAL SENSOR SET

Fault modeling for battery pack

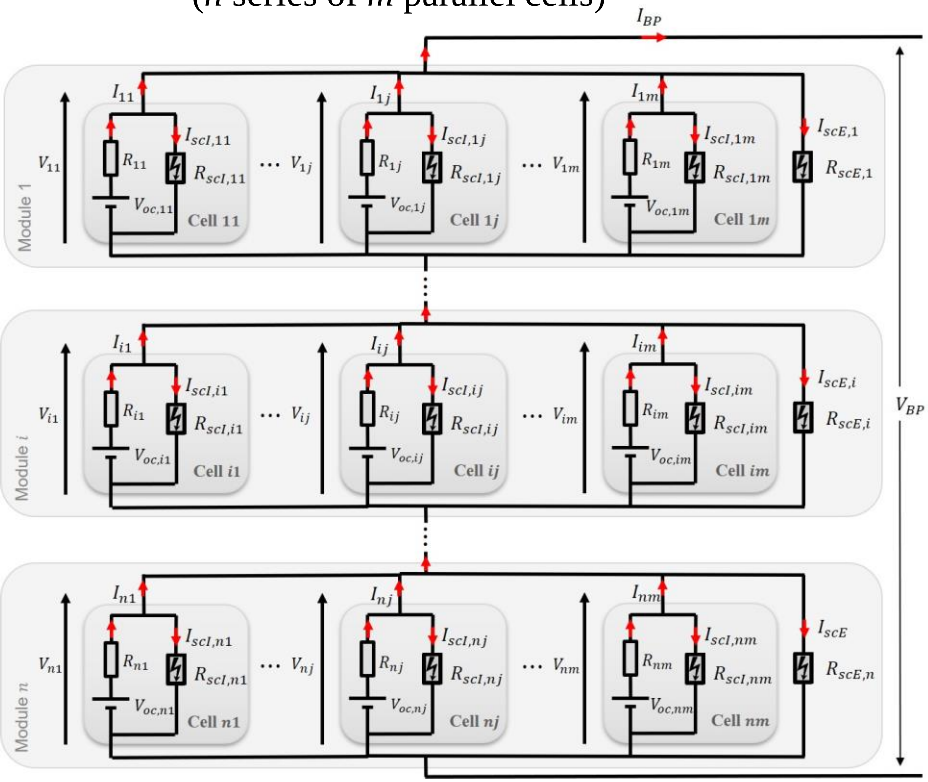
Type of faults we want to diagnose:

1. **internal short circuit** (**each cell** is modeled with an internal short circuit fault signal in it)
2. **external short circuit** (an external short circuit fault signal is modeled in **each module**)
3. **Sensor faults** (depending on the sensor set)

nSmP

(n series of m parallel cells)

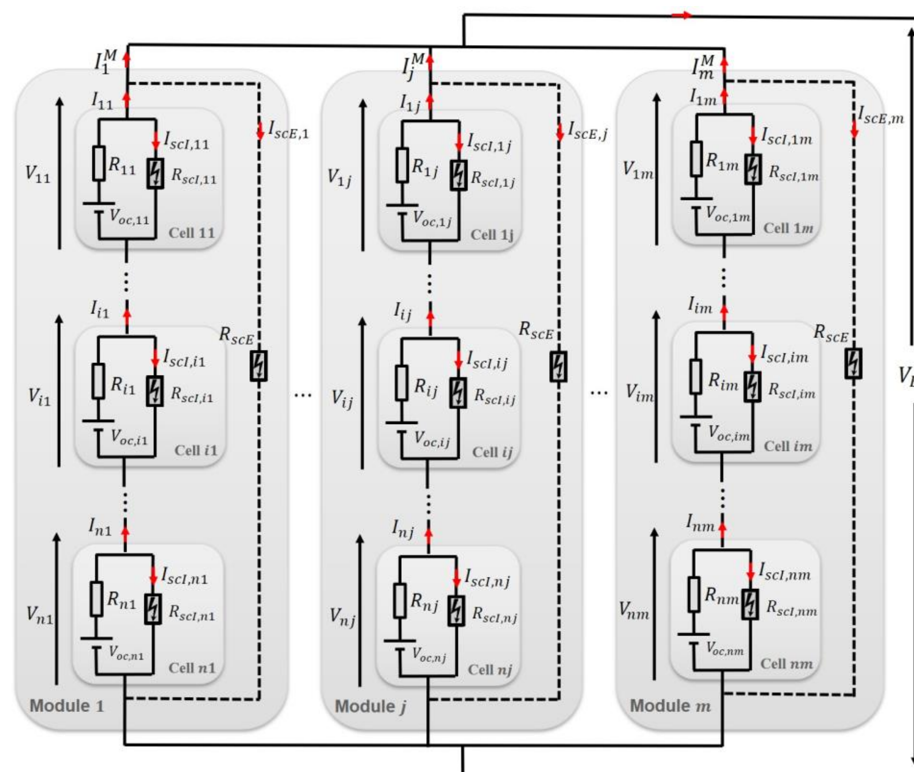
AR $= -1$



mPnS

(m parallel of n series cells)

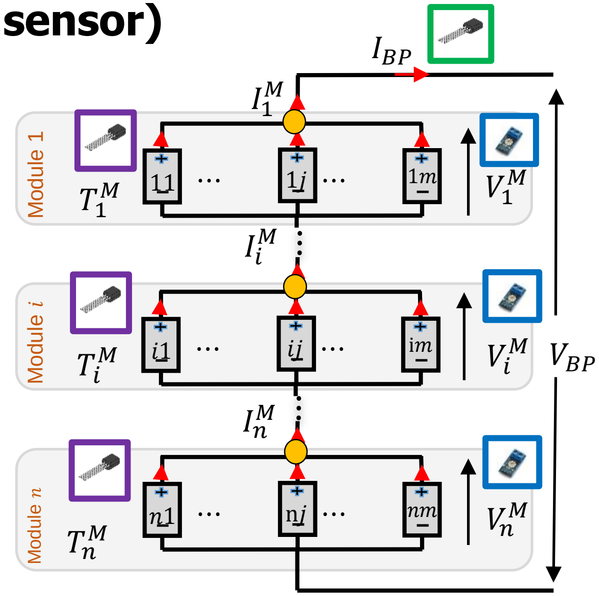
AR $= -1$



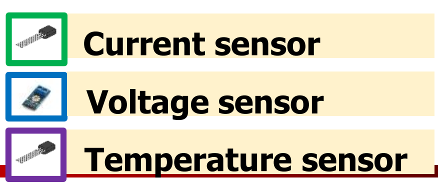
Can a **traditional sensor set** diagnose/isolate internal and external short circuit faults as well as sensors (BMS) faults?

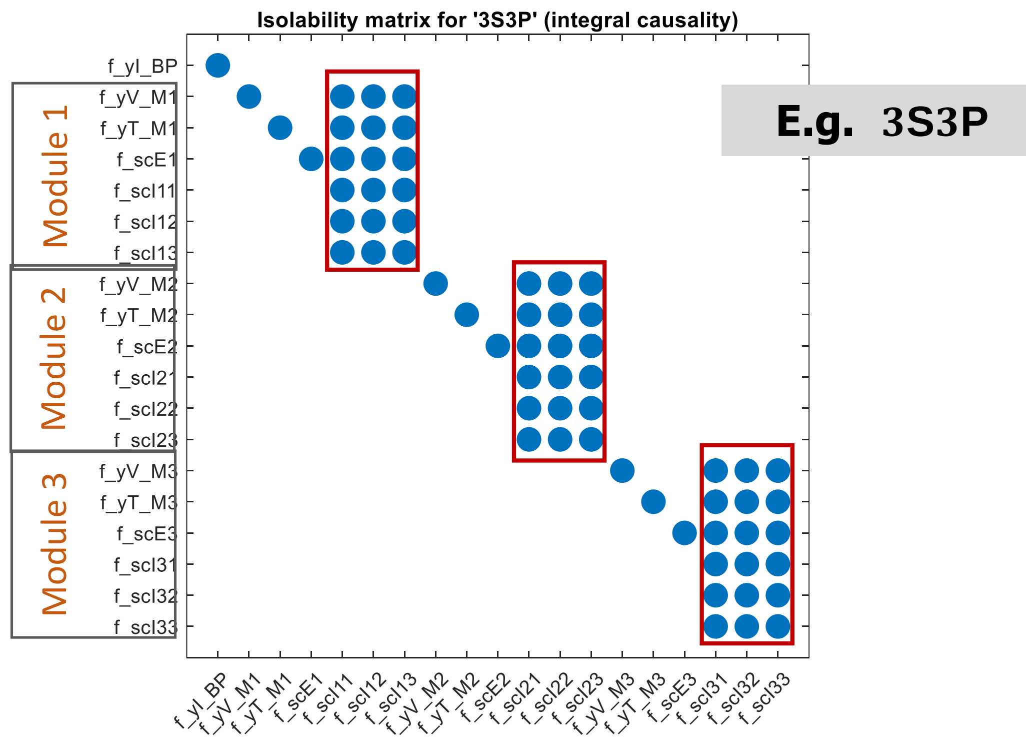
Traditional sensor set for the $nSmP$ topology battery pack:

- **a load current sensor** to measure I_{BP} .
- cells that are in parallel share a voltage sensor (**each module has a voltage sensor**).
- cells that are in parallel share a temperature sensor (**each module has a temperature sensor)**



$nSmP$
Series of parallel cells





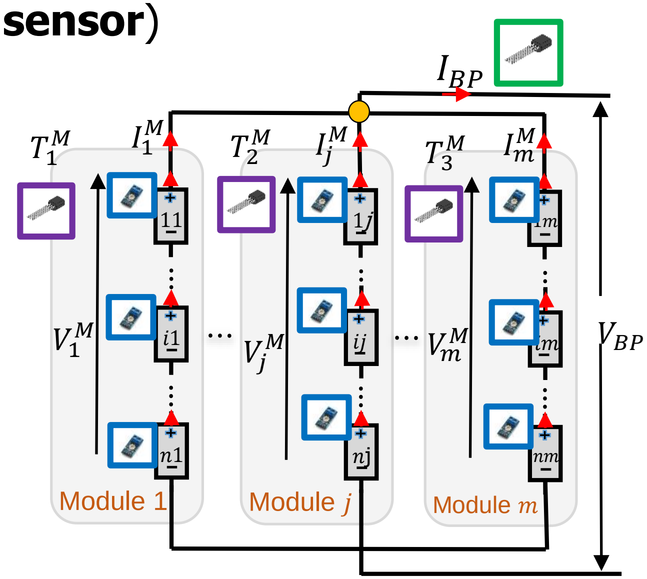
Fault isolability matrix of 3S3P topology battery pack with traditional sensor set $\{y_{I_{BP}}, y_{V_{M1}}, y_{V_{M2}}, y_{V_{M3}}, y_{T_{M1}}, y_{T_{M2}}, y_{T_{M3}}\}$

Cheng, Y., D'arpino, M., & Rizzoni, G. (2020). Structural Analysis for Fault Diagnosis and Sensor Placement in Battery Packs. *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans*, *in preparation*.

Can a traditional sensor set diagnose/isolate internal and external short circuit faults as well as sensors (BMS) faults?

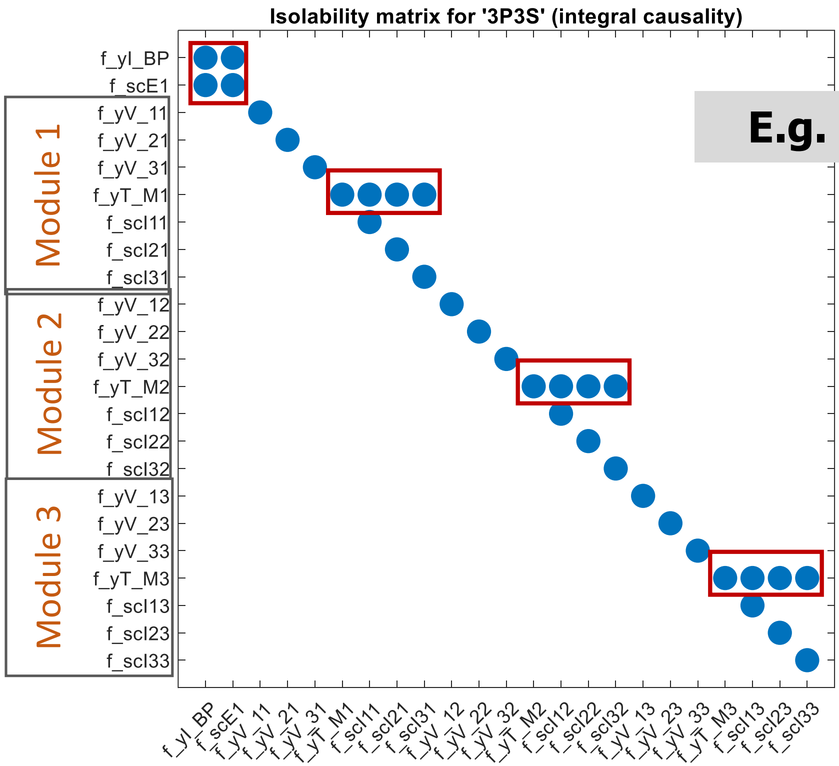
Traditional sensor set for the $m\mathrm{P}n\mathrm{S}$ topology:

- **a load current sensor** to measure I_{BP}.
- **each cell has its own voltage sensor.**
- cells that are in series share a single temperature sensor (**each module has a temperature sensor**)



$m\mathrm{P}n\mathrm{S}$

Parallel of series connected cells



Current sensor

Voltage sensor

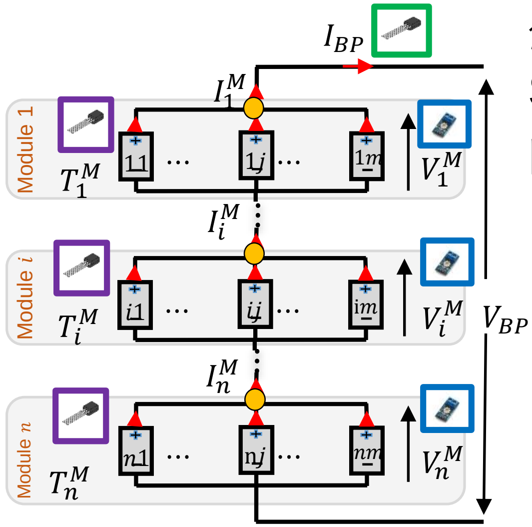
Temperature sensor

Fault isolability matrix of 3P3S topology battery pack with traditional sensor set $\left\{\begin{matrix} y_{I_{BP}}, y_{T_{M1}}, y_{T_{M2}}, y_{T_{M3}}, y_{V_{11}}, y_{V_{21}}, y_{V_{31}}, \\ y_{V_{12}}, y_{V_{22}}, y_{V_{32}}, y_{V_{13}}, y_{V_{23}}, y_{V_{33}} \end{matrix}\right\}$

Cheng, Y., D'arpino, M., & Rizzoni, G. (2020). Structural Analysis for Fault Diagnosis and Sensor Placement in Battery Packs. *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans*, *in preparation*.

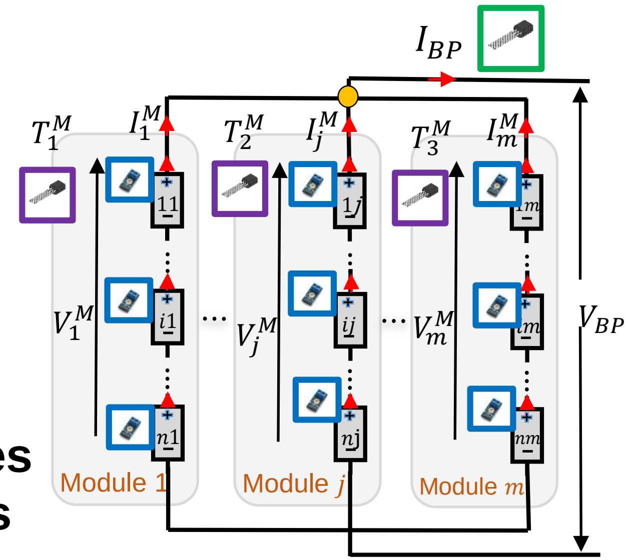
Diagnostic property of two battery pack topologies with traditianl sensor set (summary)

Can a traditional sensor set diagnose/isolate internal and external short circuit faults as well as sensors (BMS) faults?



nSmP
Series of parallel cells

mPnS
Parallel of series connected cells



# sensors: 1 pack current + n module temperatures + n module voltages (positive) **Detectability:** all the faults can be detected (positive) **Module fault isolability:** isolate faults between module (positive) **Cell fault isolability:** not allow for isolating which cell happens to be faulted in the module (negative)	**# sensors: 1 pack current + m module temperatures + $n \times m$ cell voltages** (negative) **Detectability:** all the faults can be detected (positive) **Module fault isolability:** isolate which fault is happening and in which module, except battery pack current sensor fault and the external short circuit fault (positive) **Cell fault isolability:** allow for isolating which cell happens to be faulted in the module, except the temperature sensor fault is not isolable from the internal short circuit faults. (positive)

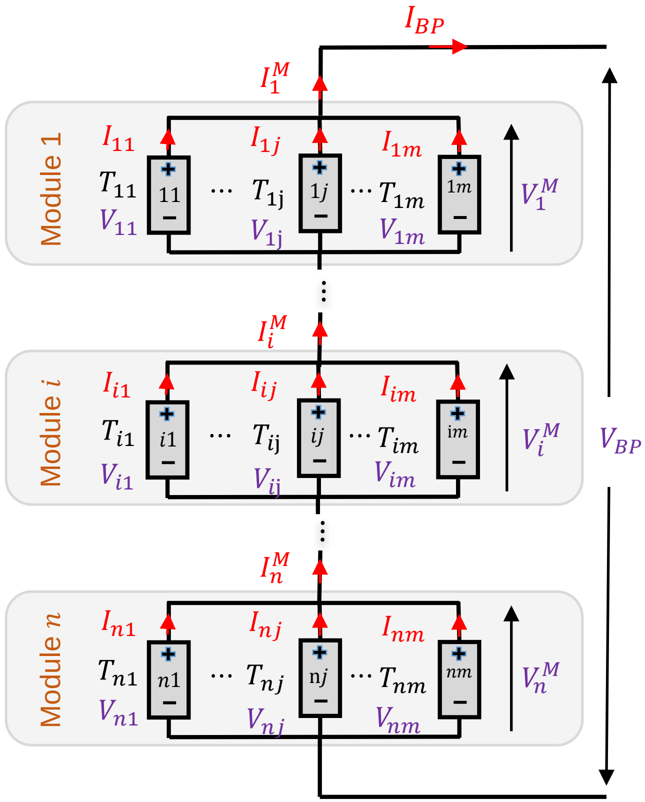
PERFORMING SENSOR PLACEMENT TO FIND MINIMAL SENSOR SET THAT CAN ACHIEVE COMPLETE FAULT ISOLATION

Possible sensor locations and types

Type of fault that we want to diagnose: internal and external short circuit, and sensor faults (sensor faults depend on the sensor set added to the system.)

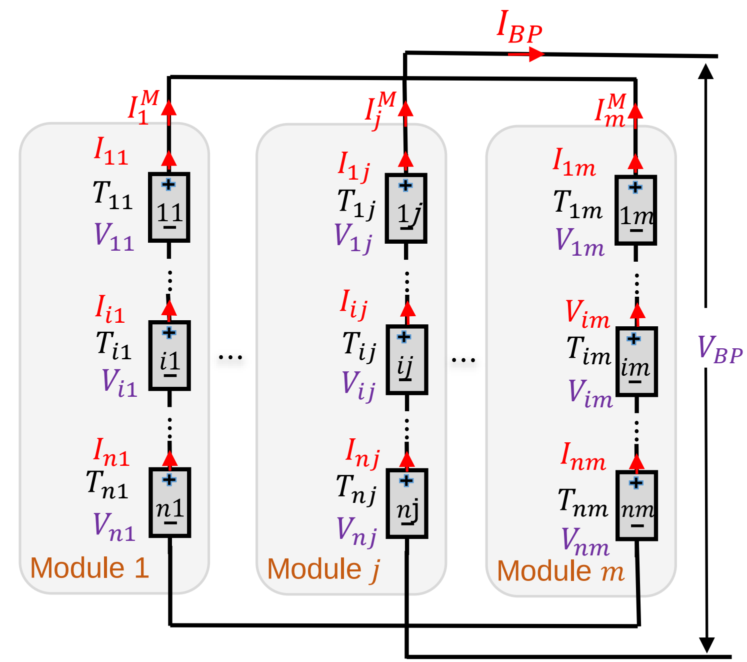
nSmP

(*n* series of *m* parallel cells)



mPnS

(*m* parallel of *n* series cells)

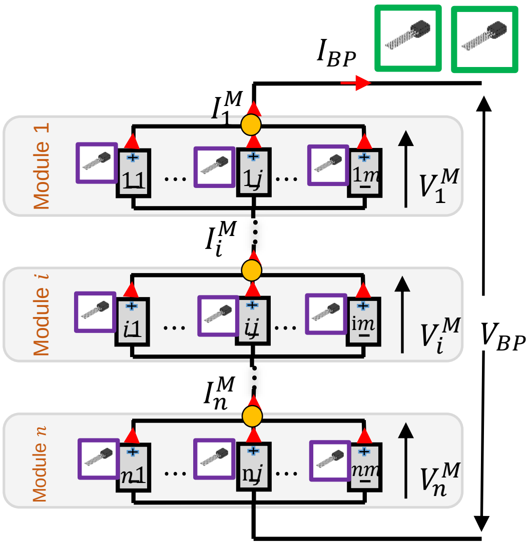


Locations: cell, module, pack
Types: current, voltage or temperature

All the possible combination of sensor set are considered

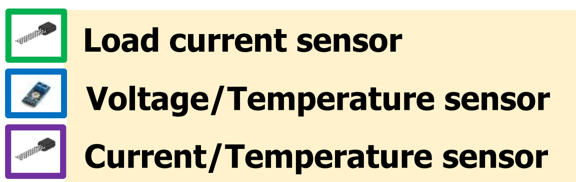
Optimal Sensor Placement for Battery Packs

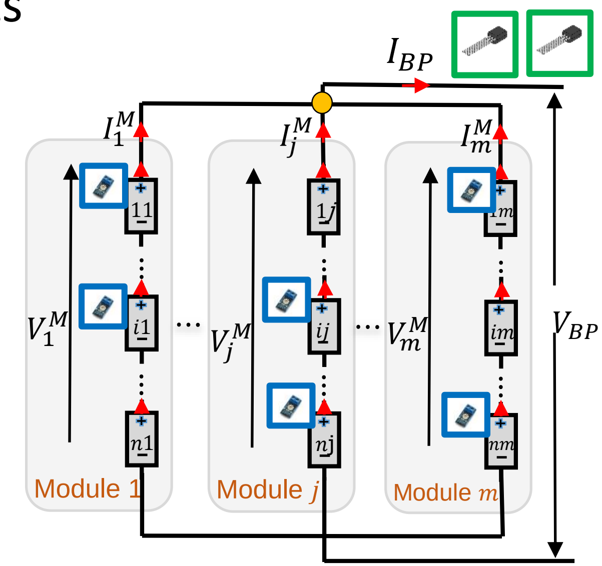
Goal: **complete detection/isolation** of internal and external short circuit conditions as well as sensors (BMS) faults, without cost constraints



$nSmP$

Series of parallel cells





$mPnS$

Parallel of series connected cells

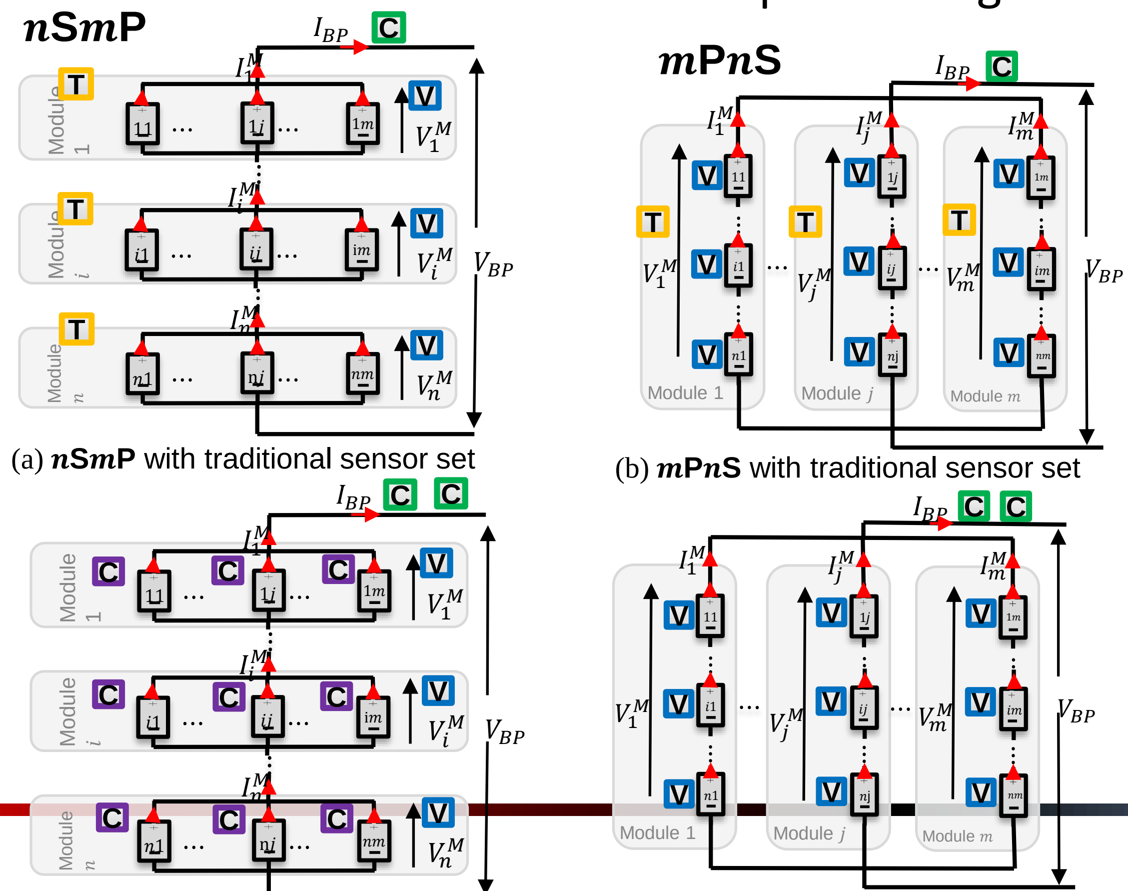
The minimum sensor set: **Module level:** Each cell should be equipped with a sensor. It could measure current or temperature. Preferred $n \cdot m$ cell current measurement (negative) **Pack level:** 2 duplicate sensors to measure battery pack current. (same) **The addition of voltage sensors doesn't help.**	**The minimum sensor set:** **Module level:** $n-1$ cells in each module should be equipped with a sensor. It could measure voltage or temperature. Preferred $(n-1) \cdot m$ cell voltage measurement (positive) **Pack level:** 2 duplicate sensors to measure battery pack current. (same) **The addition of current sensors doesn't help.**

Cheng, Y., D'Arpino, M., & Rizzoni, G. (2020). Structural Analysis for Fault Diagnosis and Sensor Placement in Battery Packs. *arXiv preprint arXiv:2008.10533*.

Conclusions

- A comparative analysis between SP and PS has been carried out
  - PS seems to have several advantages due to the fact that the entity of the fault or imbalance in case of malfunction is n times smaller than SP, however the malfunction is spread across the whole pack

- A methodology for the optimal sensor set has been proposed and compared with traditional sensor set. The team is performing further economic analysis.



(a) ***nSmP*** with traditional sensor set

(b) ***mPnS*** with traditional sensor set

(c) ***nSmP*** with optimal sensor set

(d) ***mPnS*** with optimal sensor set

Traditional set up for battery packs Having partial fault detection and isolation (FDI) capability

C Load current sensor

V Voltage sensor and hardware for voltage balancing

C Cell current sensor

T Temperature sensor

Optimal set up for battery pack Having fully fault detection and isolation (FDI) capability

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