Data Analytics of Near-Real-Time Power Flow for Distribution System Monitoring

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Outline

- Introduction / Motivation
  - Real Time Power Flow (RTPF) & Bus Load Allocation (BLA)
- Identifying Features of a Feeder with Poor BLA
  - Parameter Selection
  - Approach to Identify the Significant/Distinguishing Parameters
- Case Analysis to Pinpoint the Causes
  - Feeder by Feeder Analysis
- Summary of Findings

Introduction / Motivation

- Accurate near real time monitoring is needed for Distribution Management Systems (DMS).
- Need DSSE to provide input for DMS applications such as voltage monitoring and control.
- Power flow-based DSSE (Near real time power flow - RTPF) is used for DMS – simpler approach for SE
- Implemented by using Bus Load Allocation (BLA) procedure.

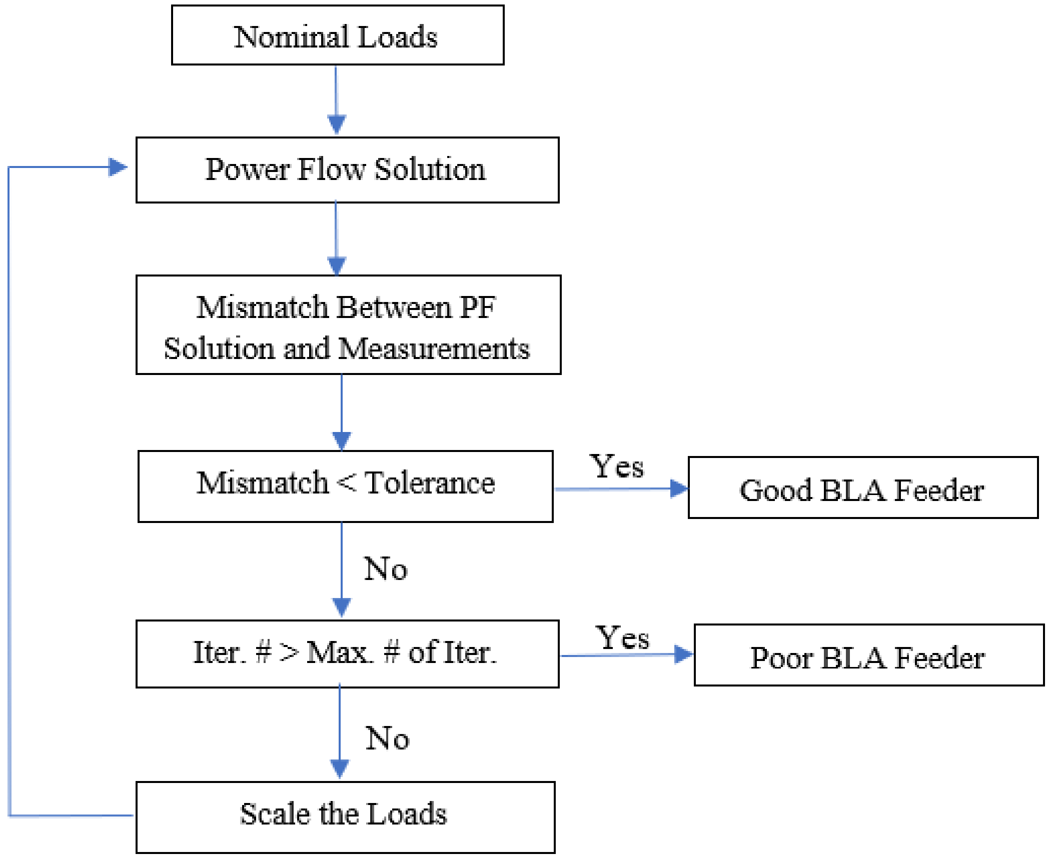
Problem:

- Near real time power flow (RTPF) - not always accurate - because of the poor load estimation obtained through the BLA procedure.
- Challenge - size and complexity of the distribution system model, and the time-consuming nature of circuit-by-circuit analysis.

Goal:

- Propose a methodology for identifying the factors that contribute to poor BLA performance on a given feeder.

DMS Real Time Power Flow (RTPF)



RTPF Flowchart

Performance Metric for RTPF

- Bus Load Allocation (BLA) convergence

BLA Convergence/Stopping Criteria	
Max # of Iterations	5
Max *P* Mismatch (kW) between Calculated and Measured	10 kW
Max *P* Mismatch (%) between Calculated and Measured	2.5 %
Max *Q* Mismatch (kVar) between Calculated and Measured	30 kVar
Max *Q* Mismatch (%) between Calculated and Measured	4 %

DMS Real Time Power Flow (RTPF)

Observation:

While BLA performance is good for most of feeders, some have poor performance consistently (we will call them as poor BLA feeders)

Stations & Savecases Provided by Duke Energy (~440 savecases total)

Consistently Good BLA Feeders	Consistently Poor BLA Feeders
AM41, WA41, WO41, WE1524, WE15R1, WE15R10, WE15R11, WE15R2, WE15R3, WE15R4, WE15R8, WE15R9, WE15W1, WE15W11, WE15W4, WE15W5, WE15W6, GM1211, DE41, DE42, DE43, DE44, DE45, DE46, DE47, DE48, KL41, KL44, KL46,LA42,LA43, LA44, LA49, TR45, TR42, TR46 ~ 400 Savecases	SB41, SB51, SB52, LA45 ~ 40 Savecases

Parameters / Features Considered

1. Total Load (kW)
2. Total Load (kVar)
3. Total Residential Load (kW)
4. Total Residential Load (kVar)
5. Total Commercial Load (kW)
6. Total Commercial Load (kVar)
7. Total Industrial Load (kW)
8. Total Industrial Load (kVar)
9. Distribution Transformer Loss (kW)
10. Distribution Transformer Loss (kVar)
11. Line Losses (kW)
12. Line Losses (kVar)
13. Shunt Capacitance (kVar)
14. Cap Injection (kVar)
15. Top of Feeder Measurement (kW)
16. Top of Feeder Measurement (kVar)
17. Total UG Cable Length (ft)
18. Total OH Line Length (ft)
19. Total 1ph Load (kW)
20. Total 1ph Load (kVar)
21. Total 2ph Load (kW)
22. Total 2ph Load (kVar)
23. Total 3ph Load (kW)
24. Total 3ph Load (kVar)
25. Number of Caps ON
26. Number of Distribution Transformer
27. Amp Flow Imbalance (%)
28. Primary Meter Load (kW)
29. Primary Meter Load (kVar)
30. Phase A Maximum Volt Drop (V)
31. Phase B Maximum Volt Drop (V)
32. Phase C Maximum Volt Drop (V)
33. Average Primary to Secondary Volt Drop (V)

Approach

- **Step 1: Logistic Regression Analysis**
  - ➢ Check if a poor BLA feeder can be separated from Good BLA feeders

    → Significant Parameters
- **Step 2: Clustering**
  - ➢ Cluster poor BLA feeders to obtain cluster based significant parameters
- **Step 3: Use significant parameters to pinpoint causes for poor BLA feeders**

Step 1: Logistic Regression Analysis

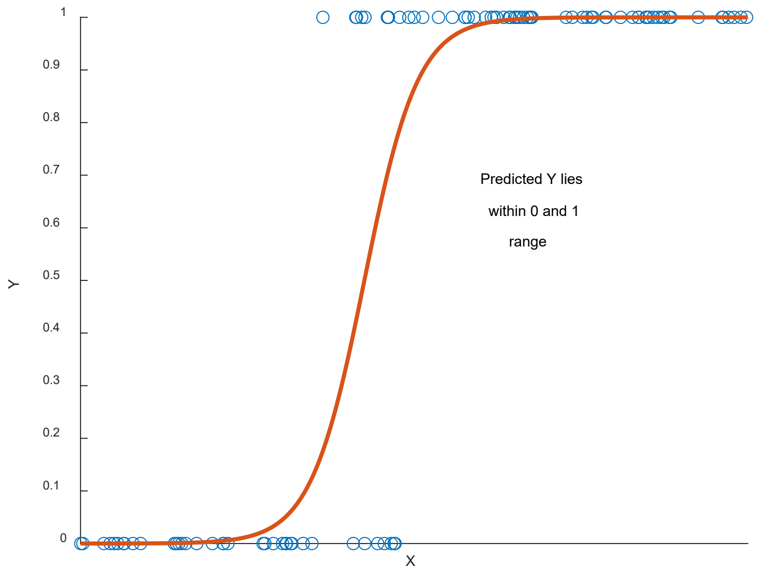
➢ *Binary Logistic Regression*

Given a set of observations with predictors (features) X, build a model that predicts outcome p

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots\dots\dots.. + \beta_n X_n$$

$$p = \frac{e^y}{1 + e^y}$$

Where X: parameters, p: outcome – Good or Poor BLA,
β : estimated coefficients based on data



➢ *Logistic Regression Benefits*

- Classification Algorithm - Predicts a binary outcome
- Identify "*significant parameters*" → Our Purpose

Step 1: Logistic Regression Analysis Results for Feeder LA45

- Used consistent savecases data (mostly Good BLA and Poor BLA feeders).
- **Distinguishing Parameters**

```
Coefficients:
                           Estimate Std. Error z value Pr(>|z|)
(Intercept)                 4.08690    1.75230   2.332  0.01968 *
Total.RES.Load...kW.      -14.51257    9.79695  -1.481  0.13852
Primary.meter.Size..kW.   -61.80011   16.14958  -3.827  0.00013 ***
Total.RES.Load...kVAR.    -32.47514   11.85130  -2.740  0.00614 **
Total.COMM.Load...kVAR.    16.38510    8.66500   1.891  0.05863 .
Total.IND.Load...kVAR.     15.18761    8.10391   1.874  0.06092 .
Total.IND.Load...kW.      -18.15733    8.38618  -2.165  0.03038 *
Line.Losses...kW.        -486.31392  291.88493  -1.666  0.09569 .
Line.Losses...kVAR.       227.33317  135.57706   1.677  0.09359 .
Top.of.Feeder.Meas...kW.   26.40834   11.16925   2.364  0.01806 *
Top.of.Feeder.Meas...kVAR.  6.71333    3.38466   1.983  0.04732 *
Cap.Injection...kVAR.     -24.64429   11.73043  -2.101  0.03565 *
Total.OH.Line.Length        4.42143    1.74896   2.528  0.01147 *
Number.of.ON.Caps          -1.63736    0.78529  -2.085  0.03707 *
Number.of.Dist.Xmr        -14.52473    6.58698  -2.205  0.02745 *
Amp.flow.imbalance..        0.04008    0.02492   1.608  0.10773
Two.Phase..kW.           -227.39235  151.02524  -1.506  0.13216
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

→ Significance Level is 0.01

Significant Parameters for Feeder LA45

1. Primary Meter Size kW
2. Total RES Load kVar

- **Performance Analysis of the Model (Confusion Matrix):**

	Predicted NC	Predicted C
Obs. NC	3	1
Obs. C	0	122

Model of the efficiency is **99.2 %**

→ Good Separation between LA45 and Good BLA Feeders

Step 1: Logistic Regression Analysis Results for Feeder SB41

- Used consistent savecases data (mostly Good BLA and Poor BLA feeders).
- **Distinguishing Parameters**

```
Coefficients:
                                                Estimate Std. Error z value Pr(>|z|)
(Intercept)                                       3.9651     1.4758   2.687 0.007215 **
Total.Load...kVAR.                              -10.6953     4.3059  -2.484 0.012997 *
Total.RES.Load...kVAR.                          -17.4742     7.0101  -2.493 0.012677 *
Total.COMM.Load...kVAR.                          26.4408     8.0880   3.269 0.001079 **
Total.COMM.Load...kW.                           -12.3453     4.6153  -2.675 0.007477 **
Line.Losses...kVAR.                             126.8896    52.2947   2.426 0.015248 *
Shunt.Capacitance..Cable.and.Line.Capacitance..kvar 77.0408 47.2296   1.631 0.102849
Top.of.Feeder.Meas...kW.                         14.1221     5.7506   2.456 0.014058 *
Total.Underground.Cable.Length                    2.3390     0.5784   4.044 5.25e-05 ***
Total.OH.Line.Length                             -2.3543     0.6776  -3.474 0.000512 ***
Number.of.ON.Caps                                -0.8626     0.3769  -2.289 0.022089 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

→ Significance Level is 0.01

Significant Parameters for Feeder SB41

1. Total UG Cable Length
2. Total OH Line Length
3. Total Commercial Load kVar
4. Total Commercial Load kW

- **Performance Analysis of the Model (Confusion Matrix):**

	Predicted NC	Predicted C
Obs. NC	3	1
Obs. C	0	122

Model of the efficiency is **99.2 %**

→ Good Separation between SB41 and Good BLA Feeders

Significant Parameters for LA45 and SB51

Distinguishing Parameters	Good BLA Feeders Average Values	LA45 Feeder Average Values
Primary Meter Size kW Load %	3.06%	58.6%
Total Residential Load kVar %	11.9%	1.3%

Distinguishing Parameters	Good BLA Feeders Average Values	SB41 Feeder Average Values
Total OH Line Length %	86%	266%
Total UG Cable Length %	85%	133%
Total Commercial Load kVar %	21%	4.6%
Total Commercial Load kW %	38%	21%

- “Total OH Line Length” and “Total UG Line Length” for feeder SB41 are quite higher than average values of Good BLA Feeders.
- LA 45 feeder is a unique feeder with a big Primary Meter Size load.

→ ***Certain combination of significant parameters contribute to Poor BLA performance***

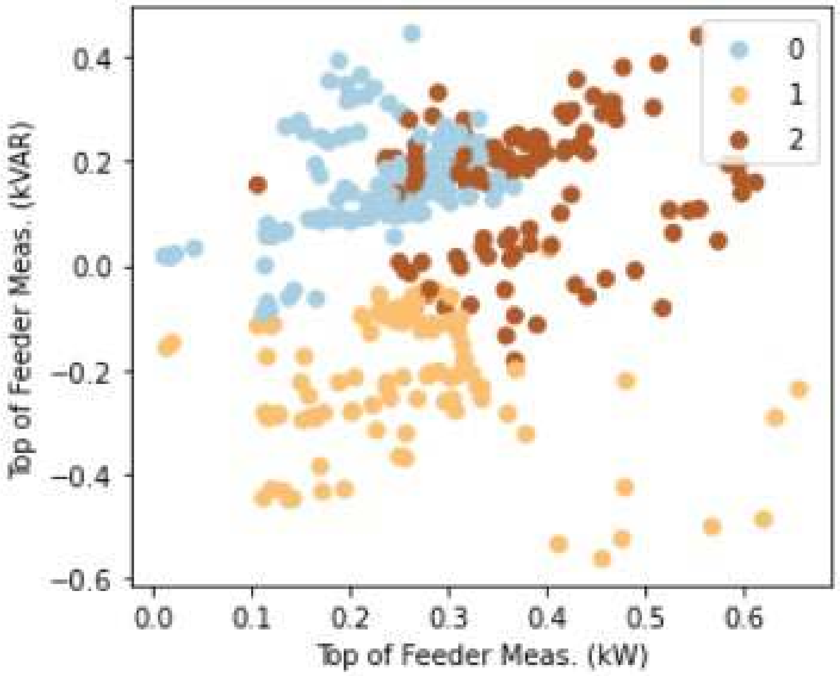
Step 2: Clustering

➢ *K-Means Clustering*

Motivation

- Given a set of features, can non-converging cases be grouped into clusters of similar characteristics and separate from converging cases?

- If so, we can examine the features that separate these clusters
  → Identify distinguishing parameters of non-converging clusters

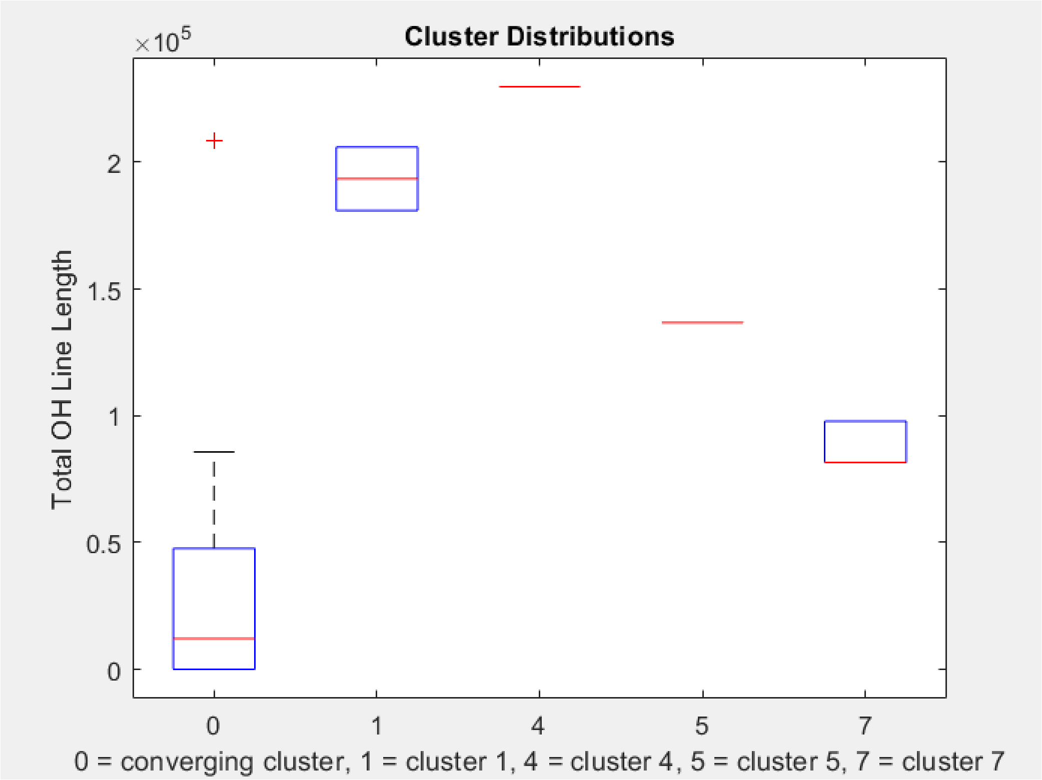


Step 2: Cluster Distinguishing Parameters

Two-Sample t-test
between non-converging clusters

- $t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$

→ Statistically determine significant parameters that separate a cluster from the other clusters



Distinguishing Parameters

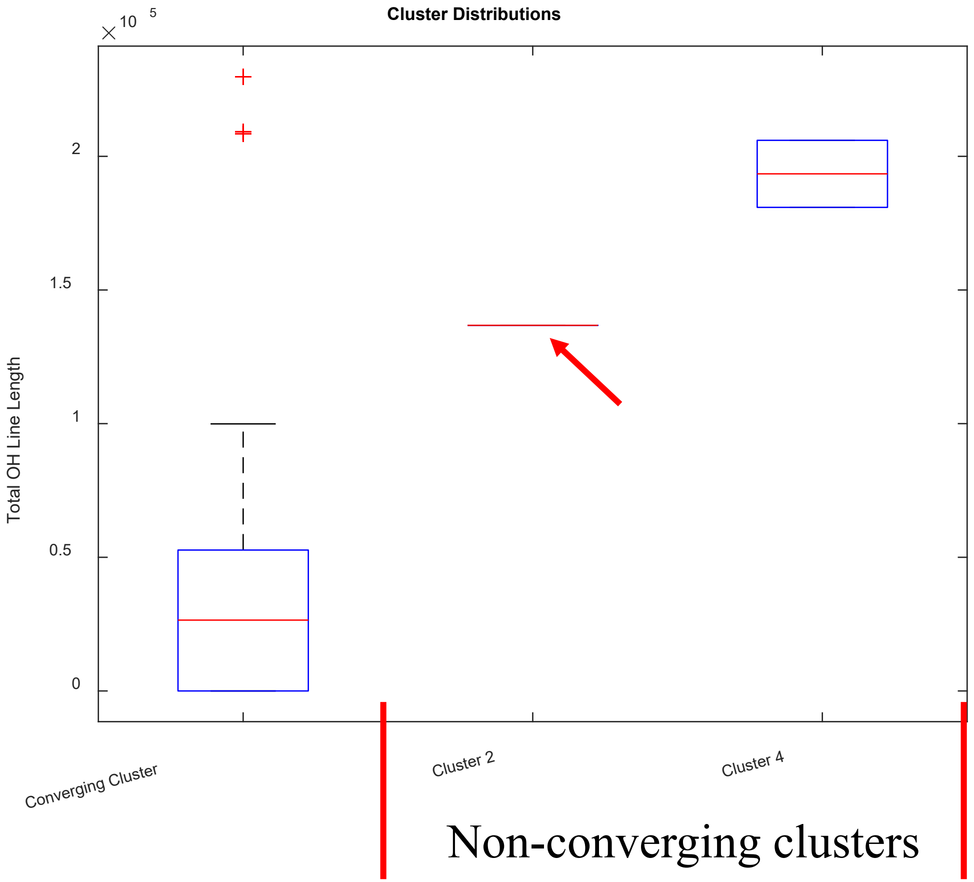
Non-converging Cluster 2 (Feeder: SB41)

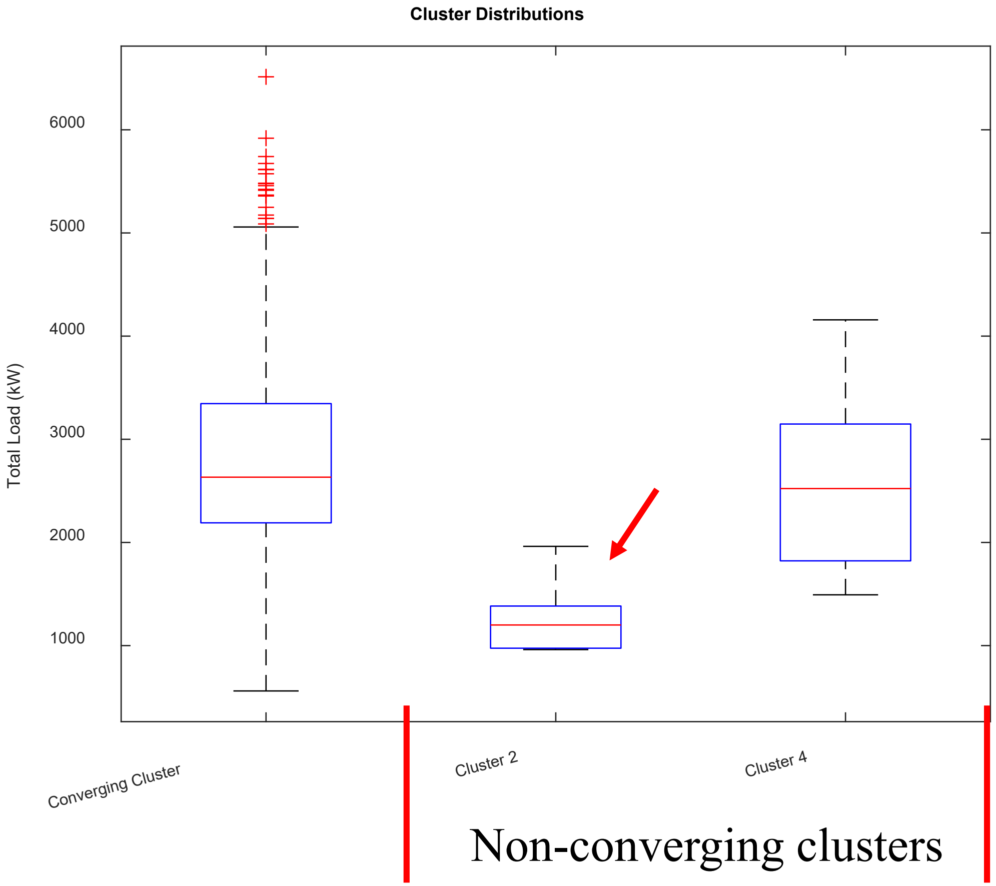
Top 6 Distinguishing Parameters	T-Statistic
1. Total OH Line Length (ft)	16.045
2. Total Two Phase Load (kW)	6.512
3. Number of Dist. Xfmr	5.537
4. Total Load (kW)	5.408
5. Total Commercial Load (kW)	5.228
6. Top of Feeder Meas. (kW)	4.8104

- Notable Distinguishing Parameters
  → High OH line length
  → Low loading

Distinguishing Parameters

Non-converging Cluster 2 (Feeder: SB41)





Distinguishing Parameters

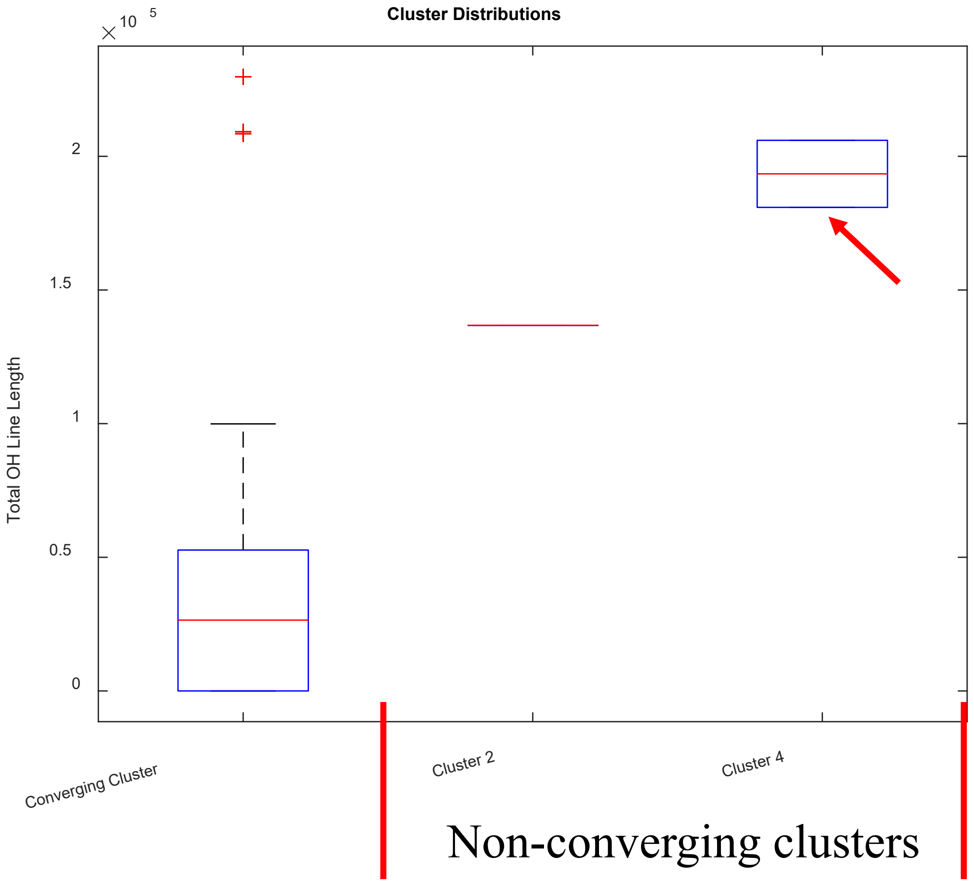
Non-converging Cluster 4 (Feeder: SB51 & SB52)

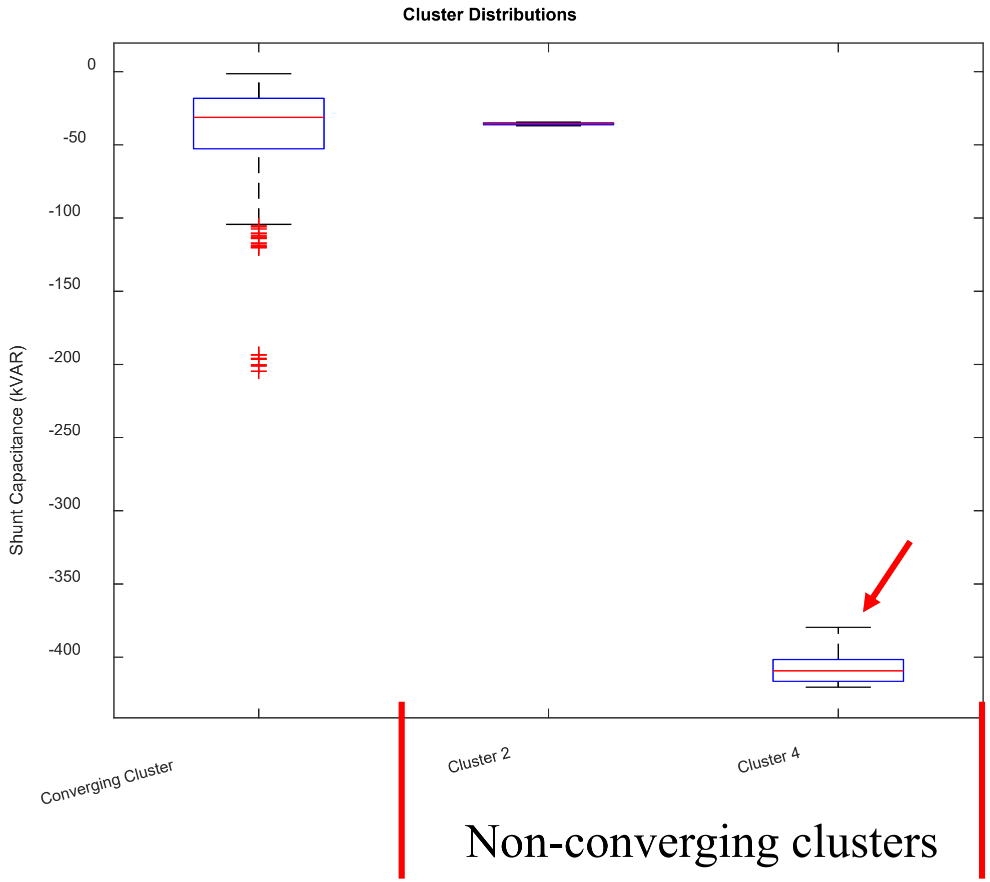
Top 6 Distinguishing Parameters	T-Statistic
1. Line/Cable Shunt Injection (kVAR)	83.769
2. Total OH Line Length (ft.)	17.500
3. Total UG Cable Length (ft.)	10.661
4. Number of Dist. Xfmr	5.537
5. Dist. Xfmr Loss (kW)	4.631
6. Top of Feeder Measurement (kVAR)	4.145

- Notable Distinguishing Parameters
  → High OH line length
  → High UG cable length
  → High line/cable shunt capacitance injection

Distinguishing Parameters

Non-converging Cluster 4 (Feeder: SB51 & SB52)





Step 3: Reasons for Poor BLA Performance

BLA Report on Non-Convergence

BLA Detailed Report is retrieved, and the reason for Poor BLA feeders is given below:

Measurement island real power converged?:	Yes
Measurement island reactive power converged?:	No
Measurement island real power potential case to be investigated?:	No
Measurement island reactive power potential case to be investigated?:	Yes
Reason:	Too little reactive power to be allocated in phase A. Review Maximum Power Factor set in DCE.
Measurement island starts from previous DPF solved load values?:	No
Number of three-phase balanced loads:	37
Number of open wye-open delta transformer bank loads:	0
Number of non three-phase balanced loads:	2
Number of phase A loads:	346
Number of phase B loads:	318
Number of phase C loads:	318

- Reason; too little reactive power to be allocated.

Step 3: Reasons for Poor BLA Performance

BLA non-convergence is due to too little reactive power to be allocated

New Metric: Total kVar Load to be Allocated:

$$Q_{alloc} = Q_{o\_feeder} - Q_{loss} - Q_{cap}$$

Where Q_{o_feeder} is measurement kVar at Feeder Head
Q_{loss} is total loss (Xmer Loss, Line Losses etc)
Q_{cap} is total capacitor injection

- Q_{alloc} is a good indicator

→ when Q_{alloc} is negative or very low it means that there is not enough kVar to be allocated.

→ when Q_{alloc} is low, BLA cannot adjust kVar of the loads given the pf constraints.

Step 3: Feeder by Feeder Analysis – SB41

Goal - Use the significant parameters to pinpoint the possible cause(s) for a consistent poor BLA feeder

Save Case Day	Total kW Load	Total kVar Load	Dist. Xmer Losses kVar wrt Total Load KVA (%)	Line Losses kVar wrt Total OH Line Length (%)	Cable and Line Capacitance kVar wrt UG Cable Length (%)	Total kVar Losses	Total kVar Losses wrt Total Load KVA %	Cap Injection kVar	Top of Feeder Measure ment kVar	kVar Mismatch (Calculated – Measurement)	Total kVar Load to be Allocated (Q_{aloc})
3/17 4 pm	1314.76	121.35	18.1%	0.005%	0.10%	209.51	15.9%	-1419.57	-1339	250.29	-128.9
3/17 2 pm	1397.54	133.45	16.9%	0.005%	0.09%	209.34	14.9%	-1412.2	-1311	241.59	-108.1
5/24 11 am	1369.62	212.41	16.9%	0.006%	0.09%	207.38	15%	-1393.94	-1130	155.85	56.56
3/17 9 am	1962.12	183.66	12%	0.013%	0.09%	220.92	11.2%	-1399.47	-1207	212.11	-28.45
3/17 11 am	1771.23	148.09	13.3%	0.010%	0.09%	215.49	12.1%	-1400.22	-1260	223.36	-75.27
5/13 4 pm	988.33	125.76	23.9%	0.004%	0.10%	207.27	20.8%	-1422.08	-1322	232.95	-107.2
5/20 10 am	961.45	30.26	24.8%	0.004%	0.10%	206.87	21.5%	-1262.57	-1272	246.56	-216
4/24 4 pm	1510.74	162.35	15.7%	0.006%	0.09%	212.52	14%	-1419.27	-1273	228.6	-66.25
4/26 3 pm	961.25	155.35	24.5%	0.003%	0.10%	205.61	21.1%	-158.69	-3	205.27	-49.92
4/29 1 pm	1085.08	147.45	21.9%	0.004%	0.10%	209.19	19.1%	-1428.05	-1284	212.59	-65.14

- Negative Q_{alloc}
- High total kVar Losses / Total Load KVA (Average of Good BLA feeders is 7.8%)
- High Distribution Transformer kVar losses / Total Load KVA, partly due to being a long feeder (a distinguishing parameter) with mostly residential loads served by single phase transformers.
- High Single Phase Distribution Transformers (distinguishing parameter)

Conclusions

- Developed a method for feature extraction
  - Logistic Regression Analysis
    - → identify *significant parameters* for poor BLA feeders
  - Cluster Analysis
    - →Identify poor BLA feeders that are “similar”
    - →Identify distinguishing parameters for each cluster
- Detail Feeder Analysis
  - → Pinpoint the cause(s)

Questions?

Thank you!