An Analysis of DMS Power Flow Performance

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***Abstract*— The continuous modernization of the electric power grid, including the increased adoption of distributed energy resources and of remotely monitored and controlled devices, has brought about an augmented use of distribution automation and Advanced Distribution Management Systems (ADMS) applications. These tools can help improve grid reliability and ensure optimal grid operation. Several distribution system closed-loop controllers with applications such as Integrated Volt/Var control rely on power flow results to make grid optimization decisions. Hence, the accuracy of the power flow results is of paramount importance for appropriate informed decision-making. This paper presents an analysis of the Distribution Management System (DMS) power flow performance, including a selection of appropriate performance metrics. The selected performance metrics are used to detect and analyze inaccuracies in DMS power flow results. The investigation is carried out on near-real-time power flow results from multiple substations obtained from a utility company. The substation models and SCADA measurements were also used in the analysis. It is envisioned that this power flow performance analysis can help guide further studies to identify causes of poor power flow performance and mitigate them.**

Keywords*— *distribution power flow, distribution network, distribution management system, near real-time power flow

I. Introduction

A Distribution Management System (DMS) monitors, controls, and optimizes the distribution grid; it estimates the state of the system utilizing the distribution feeder model, device status, and available field measurements. It can present advanced capabilities, including enabling reconfiguration of the network topology, regulation of the voltage profile, identification, and isolation of faulted lines [1]. Applications such as Integrated Volt/Var Control (IVVC) rely on Distribution Power Flow (DPF) results to make grid optimization decisions [2][3][4]. Accurate DPF results are then critical to operate the power grid safely and efficiently, especially considering the added challenges presented by increased integration of Distributed Energy Resources (DER) and adoption of demand response services. Unfortunately, power flow results are not always accurate, and existing methods of analysis regularly fail to determine the cause of the inaccuracy due to the size of the network, complexity of the DMS and difficulty in accurately representing system components (including DERs, lines, capacitor banks, and other network equipment). However, DPF with properly developed load allocation functionality could help resolve some of the inaccuracies associated with vast numbers of pseudo measurements [4].

Some efforts have been carried out in improving the performance of DMS power flow [5][6]. The focus thus far has been on circuit-by-circuit or substation-by-substation in-depth analysis at a few individual points in time. This approach has significant limitations; it lacks a holistic view of possible problems and struggles to identify trends over time. It is necessary to focus on trending metrics that may be a secondary or tertiary result of the real issue - symptoms, not problems.

The work presented in this paper is part of a collaborative project with a utility company, Duke Energy. The project focuses on developing a greater understanding of the strengths and weaknesses of the distribution power flow algorithm used by the DMS and then identifying and mitigating causes of poor power flow performance. In this paper, a set of measurable metrics is developed to define the accuracy of DPF solutions. The formulated metrics are then used to analyze the performance of actual power flow cases provided by the utility. It is envisioned that the findings in this paper can inform the development of data analytics tools to parse through DPF save cases and identify significant factors indicating poor power flow performance.

The paper is organized as follows: Section II describes the methodology used in the performance analysis and introduces the metrics of evaluation; results and observations are presented in Section III; the paper then concludes and briefly discusses ongoing and future work in Section IV.

II. Methodology

A. DPF and BLA Description

DPF can be described as a combination of conventional power flow formulated for distribution system scenarios and real time measurements. Typically, loads in DPF can be estimated with state estimation method or allocation method [4]; state estimation method is used in Energy Management Systems (EMS) to obtain the best estimate for the bus voltages and angles [5]. However, for distribution management systems, a state estimation method has been proposed in [6][7], but the practical application comes with several challenges such as unbalanced operation, the vast number of pseudo-measurements required [8] [9], and network configuration problems [10]. In addition, a majority of the measurements are in amperes only, and there are difficulties in parameter tuning. Due to the challenges that accompany state estimation methods, the DMS under study uses a simpler load allocation method known as BLA. This procedure scales the loads to match the available real-time measurements.

The distribution power flow calculates the complex voltages at all the feeder nodes and subsequently the power flowing through all feeder segments. The BLA function is executed together with the DPF, it estimates the real and reactive loads at the feeder node; for each save case, it ensures that the load and the network topology are consistent with metered flows, current breaker statuses and metered loads. Fig. 1 gives a graphical depiction of the DMS power flow process.

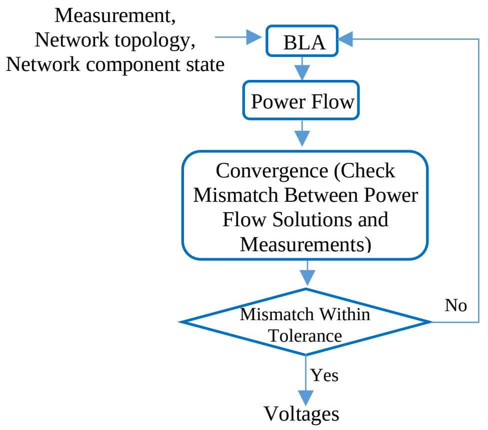

Fig. 1. Overview of a DMS Power Flow Process

B. Data and Model Description

The analysis was performed on real substation models provided by the utility company. The dataset comprised of 13 different substations with each substation having multiple feeders. Several save cases were obtained for each substation. A save case is a file which contains the system configuration, such as switch statuses, and available measurements at a particular timestamp. The save cases also contain geographical information provided by the utility. The save cases were opened on the DMS software, and other power system software.

The substations examined in this paper were classified into two network regions and will henceforth be called Region A and Region B for reasons of anonymity. This classification is based on physical locations and operation region. In addition, different power flow convergence criteria are adopted in the two regions. The convergence criteria employed in these regions will be described in the DPF and Bus Load Allocation (BLA) description in section II (A).

The convergence criterion for substation A is Bus Load Allocation (BLA) convergence while the convergence criterion for Area B is voltage mismatch. For instance, if the BLA of a save case in Region A converges, then the save case is considered to have converged. Similarly, a save case in Region B is regarded as a converging save case if the voltage mismatch is within the 3V threshold. Based on the respective convergence criteria, the substations that frequently converge are considered as converging substations while substations that seldomly converge are considered as non-converging substations.

The performance of the save cases is further analyzed in section III based on the metrics.

C. Performance Metrics

The power flow performance metrics define the accuracy of the power flow algorithm.

<u>BLA Convergence</u>: The conditions for the BLA convergence metric have both real power and reactive power thresholds. BLA converges if the real power and reactive power mismatch is less than a specified mismatch threshold before the end of the specified number of iterations. Table I summarizes the BLA convergence metrics used in this work. The threshold is a fixed value and a percentage of the measured power values. Equation (1) and Equation (2) describe the mismatch and percentage mismatch respectively. For a good performing save case, the BLA is expected to converge based on the defined thresholds.

TABLE I. BUS LOAD ALLOCATION CONVERGENCE/STOPPING CRITERIA

Max # of Iterations	5
Max P Mismatch (kW) between Calculated and Measured	10 kW
Max P Mismatch (%) between Calculated and Measured	2.50%
Max Q Mismatch (kVar) between Calculated and Measured	30 kVar
Max Q Mismatch (%) between Calculated and Measured	4%

$$P_{mismatch} = P_{calculated} - P_{measured}$$
$$Q_{mismatch} = Q_{calculated} - Q_{measured} \quad (1)$$

$$\%P_{mismatch} = \frac{P_{mismatch}}{P_{measured}}$$
$$\%Q_{mismatch} = \frac{Q_{mismatch}}{Q_{measured}} \quad (2)$$

<u>Voltage Mismatch</u>: the voltage mismatch is described by (3). It is the difference between the calculated and measured voltages. The calculated voltage is the bus voltage calculated by the power flow while the measured voltage is the voltage from the network measurement devices. The performance metric is determined if the voltage mismatch is within a specified threshold. For a good- performing power flow algorithm, 99% of the measurement nodes should have a voltage mismatch that is less than 3V.

$$V_{mismatch} = V_{calculated} - V_{measured} \quad (3)$$

<u>Power Balance</u>: Since the power flow solution of a power system involves calculating a mismatch at every step of the iteration (e.g., Newton Raphson Method), the power balance metric is based on the mismatch at the end of the power flow solution. The percentage difference in feeder head power flow and sum of the loads including feeder loss is benchmarked against the feeder load, as described in (4).

$$\%P_{mismatch} = \frac{(P_{feeder} - P_{load} - P_{losses} - P_{DER})}{P_{load}} \quad (4)$$
$$\%Q_{mismatch} = \frac{(Q_{feeder} - Q_{load} - Q_{losses} - Q_{capacitor})}{P_{load}}$$

Ideally, the power balance of a power flow algorithm should be 0%. This is because the calculated power at the feeder head will reflect the cumulative sum of loads, the feeder losses, the DER, and the capacitor injections and thus the numerator should be a small value.

III. Result Analysis and Interpretation

Having discussed the approaches to the investigations, the results are presented and analyzed in this section. To gain insight into the differences between the converging and non-converging substations, the result of a set of converging substations was compared to a set of non-converging substations for each network area. The comparison was based on the three performance metrics.

A. Power Flow Results

A typical representation of the power flow results of a selected save case is shown in Table II. Each of the feeders in the substations is represented and analyzed separately. All measurements are three-phase. The distribution transformer losses are associated to distribution transformers while the line loss and shunt capacitance are associated with both overhead line and underground cable.

TABLE II. Power Flow Results for an Example Save Case (One Station with Two Feeders)

	Feeder 1		**Feeder 2**	
	kW	**kVAR**	**kW**	**kVAR**
Feeder head Power Flows	3048.95	-483.31	4878.76	9.79
Loads	2943.22	384.46	2272.29	1088.24
Capacitor value		-1217.88		-1225.63
DER	-50		-50	
Distribution transformer losses	118.03	294.17	46.45	135.46
Line Losses	35.4	80.6	21.7	30.5
Shunt Capacitance		-21.5		-18.1

The performance metrics of the selected save case are summarized in Table III. The real and reactive power BLA of feeder 1 converged, while only the active power BLA converged for feeder 2. In addition, the power balance of both feeders is less than 1%, and the voltage mismatch of feeder 1 is 0%, while the voltage mismatch of feeder 2 is 8.3%. A summary of the performance of the substations is described in section B.

TABLE III. Performance Metrics for the Example Save Case (Table II)

	Feeder 1		**Feeder 2**	
	kW	**kVAR**	**kW**	**kVAR**
BLA Convergence	YES	YES	YES	NO
% Power Balance	0.079%	-0.822%	0.028%	-0.062%
% Measurement nodes w/ voltage mismatches > 3V	0%		8.3%	

B. Performance Metric: BLA Convergence and Power to be Allocated

The BLA convergence results are presented in Tables IV - VIII, the results for all the save cases are summarized based on substations. Tables IV and V show the BLA convergence for the converging and non-converging substations in region A. For the converging stations (Table IV), 100% of the save cases in the four substations under study has a converged active power BLA. Similarly, 100% of the save cases in three out of the four substations under study has a converged reactive power BLA, one substation has a 92% BLA convergence rate.

TABLE IV. Converging Stations in Region A

Substations	**% Save cases with Converging BLA (Active power)**	**% Save cases with Converging BLA (Reactive power)**
Station 5	100%	92%
Station 7	100%	100%
Station 8	100%	100%
Station 9	100%	100%

For the non-converging stations (Table V), 100% of the save cases in the four substations under study has a converged active power BLA while less than 50% of the save cases in each of the substation has a converged reactive power BLA. The results align with the convergence criteria given by the utility.

TABLE V. Non-Converging Stations in Region A

Substations	**% Save cases with Converging BLA (Active power)**	**% Save cases with Converging BLA (Reactive power)**
Station 2	100%	0%
Station 3	100%	50%
Station 4	100%	50%
Station 6	100%	0%

Tables VI and VII show the BLA convergence for the converging, and non-converging substations in region B; most of the substation save cases in this region exhibit BLA non convergence for both active and reactive power. As mentioned in section II (B), it should be noted that in Region B the substations defined as converging, i.e. good-performing substations, are defined as such because of their performance in terms of voltage mismatch, not in terms of their BLA performance.

TABLE VI. Converging Stations in Region B

Substations	**% Save cases with Converging BLA (Active power)**	**% Save cases with Converging BLA (Reactive power)**
Station 1	100%	54%
Station 4	80%	20%

TABLE VII. Non-Converging Stations in Region B

Substations	**% Save cases with Converging BLA (Active power)**	**% Save cases with Converging BLA (Reactive power)**
Station 2	54%	0%
Station 3	79%	67%

In region B, a difference in the performance of substations with and without high DER penetration was noted. Table VIII shows the BLA convergence for save cases without (w/o) and with (w/) DERs; 100% of save cases without DERs exhibit active power BLA convergence. A strong differentiation in reactive power BLA convergence between substations with and without DERs was not observed.

TABLE VIII. NON-CONVERGING STATIONS IN REGION B W/ AND W/O DERS

	% Save cases with Converging BLA (w/o DER)	% Save cases with Converging BLA (w/ DER)
kW	100%	68%
kVAR	28%	26%

In summary, by looking at the performance of save cases with respect to the BLA convergence metric, it can be noted that the model reactive power and the presence of DERs contribute significantly to power flow performance.

In order to investigate the cause of BLA non-convergence, the active and reactive power available to be allocated to the loads was calculated using (5). The amount of power to be allocated to the loads (S_{load_alloc}) is the difference in feeder head power flow (S_{feeder}) and the cumulative sum of all the power injected by the capacitor bank (S_{cap_bank}), DERs (S_{DER}), and the line losses (S_{line_loss}) in the network. It was observed that most of the save cases with low or negative S_{load_alloc} exhibited BLA non-convergence.

$$S_{load\_alloc} = S_{feeder} + S_{cap\_bank} + S_{DER} + S_{line\_loss} \qquad (5)$$

C. Performance Metric: Power Balance

The average power balance of all the save cases is summarized based on substation; the average power imbalance and the maximum power imbalance are presented. Table IX and Table X show the power balance results for converging stations and non-converging stations, respectively in Region A. The active power imbalance of both the converging and non-converging stations is significantly less than the reactive power imbalance.

TABLE IX. POWER BALANCE RESULTS FOR CONVERGING STATIONS IN REGION A

	Real Power Imbalance		Reactive Power Imbalance	
Substations	**Average**	**Maximum**	**Average**	**Maximum**
Station 1	0.15%	0.20%	0.34%	0.42%
Station 5	4.36%	25.22%	9.28%	116.85%
Station 7	0.14%	0.29%	0.62%	1.24%
Station 8	0.10%	0.28%	0.44%	0.78%
Station 9	0.03%	0.06%	1.07%	6.66%

TABLE X. POWER BALANCE RESULTS FOR NON-CONVERGING STATIONS IN REGION A

	Real Power Imbalance		Reactive Power Imbalance	
Substations	**Average**	**Maximum**	**Average**	**Maximum**
Station 2	0.25%	0.26%	1.43%	1.44%
Station 3	0.58%	0.91%	1.12%	1.74%
Station 4	0.10%	0.19%	2.40%	3.78%
Station 6	26.19%	80.20%	19.50%	76.69%

Table XI and Table XII show the power balance results for converging stations and non-converging stations respectively in network Region B. Like Region A, the active power imbalance of both the converging and non-converging stations in Region B are significantly less than the reactive power imbalance. This metric shows that the reactive power component of the model need more detailed analysis because they contribute significantly to power flow inaccuracies.

TABLE XI. POWER BALANCE RESULTS FOR CONVERGING STATIONS IN REGION B

	Real power		Reactive power	
Substations	**Average**	**Maximum**	**Average**	**Maximum**
Station 1	0.11%	0.51%	8.05%	16.60%
Station 4	0.99%	16.41%	26.62%	79.46%

TABLE XII. POWER BALANCE RESULTS FOR NON-CONVERGING STATIONS IN REGION B

	Real Power		Reactive Power	
Substations	**Average**	**Maximum**	**Average**	**Maximum**
Station 2	5.34%	53.26%	49.11%	113.96%
Station 3	0.17%	0.71%	16.08%	82.56%

D. Performance Metric: Voltage Mismatch

Thresholds of 2V and 3V were taken into account when considering voltage mismatches. Tables XIII through XVI show the percentage of save cases that exhibit voltage mismatches greater than those two thresholds. Tables XIII and XIV refer to Region A, converging and non-converging stations, respectively, while Tables XV and XVI are for Region B converging and non-converging stations, respectively. In Region A, both the converging and non-converging stations present save cases with voltage mismatches greater than both thresholds, while in region B only stations defined as non-converging exhibit voltage mismatches. As mentioned previously, it is noted that in Region A, the substations defined as converging, i.e. with generally good-performing power flow, are defined as such based on their BLA convergence, not in terms of their voltage mismatches.

TABLE XIII. VOLTAGE MISMATCH FOR CONVERGING STATIONS IN REGION A

Substation	% Save cases with Voltage mismatch > 2V	% Save cases with Voltage mismatch > 3V
Station 2	14%	3%
Station 6	44%	28%

TABLE XIV. VOLTAGE MISMATCH FOR NON-CONVERGING STATIONS IN REGION A

Substation	% Save cases with Voltage mismatch > 2V	% Save cases with Voltage mismatch > 3V
Station 1	25%	15%
Station 9	58%	45%
Station 7	40%	29%
Station 5	29%	14%

TABLE XV. VOLTAGE MISMATCH FOR CONVERGING STATIONS IN REGION B

Substation	% Save cases with Voltage mismatch > 2V	% Save cases with Voltage mismatch > 3V
Station 1	0.0%	0.0%
Station 4	0.0%	0.0%

TABLE XVI. VOLTAGE MISMATCH FOR NON-CONVERGING STATIONS IN REGION B

Substation	% Save cases with Voltage mismatch > 2V	% Save cases with Voltage mismatch > 3V
Station 2	43.0%	15.0%
Station 3	15.9%	7.8%

The power balance and BLA metrics indicated significant inaccuracies associated to the reactive power and DERs in the networks. Typically, Inverter based DER characteristics are dependent on their control architecture [11], hence if not modelled appropriately, it could be a source of error. However, a detailed verification of the network model was done to gain more insight.

E. Network Model Verification

A comparative analysis was performed between the DMS tool and other offline power flow software tools, e.g. CYME and OpenDSS. Table XVII shows example results of the percentage power balance metric for the DMS software and another power flow software tool. Since the performance of the power flow results from the offline power system software is consistently good based on the defined metrics, the power system software result serves as the reference for comparison.

TABLE XVII. POWER BALANCE COMPARISON BETWEEN DMS AND POWER SYSTEM SOFTWARE

	DMS		**Power System Software**	
Substation Feeders	**Real Power**	**Reactive Power**	**Real Power**	**Reactive Power**
Feeder A	0.24%	49.54%	0.00%	0.00%
Feeder B	0.21%	53.85%	0.02%	0.23%
Feeder C	0.19%	28.14%	0.00%	0.00%

The network components on the two software were compared; the total number, rating, and status (ON or OFF) of system components such as loads, capacitor banks, and DERs were compared. In addition, the transformers (including rating and number of distribution transformers), voltage regulators and line model (including length, and unit impedance) were compared.

Although differences existed between the DMS and the power system software model, emphasis was placed on the line modeling because the model and status of other components could be aligned manually. The verification of the line model was done by comparing the line model parameters in the DMS software with textbook parameters [12], the line impedance was also calculated using standard calculations from the textbook and compared with line model impedance values in the DMS software.

Line Model: The line impedance in DMS was compared to a hand-calculated impedance for overhead lines and underground cables. For the "hand-calculation", three different substations were analyzed and about five lines were selected in each substation. The hand-calculation was done using the network model line parameters. However, the phase and sequence impedances of both the hand-calculation and the impedance obtained from the model matches. With this verification, it was concluded that the line impedance modelling on the DMS software is accurate; however more verification needs to be done on the validity of the line parameters imported from GIS.

IV. CONCLUSION AND FUTURE WORK

This paper investigated inaccuracies in DMS power flow solutions. Metrics of load allocation convergence, power balance, and voltage mismatch were used to analyze the performance of actual near real-time power flow cases obtained from the utility. From the results, particularly based on bus load allocation convergence and power balance, it was noted that poor power flow performance could be linked to challenges with the reactive power allocation and calculation, and with the presence of DERs. Accuracy of the models of distribution system components, including overhead and underground lines, transformers, capacitor banks, loads, and DERs, were also verified. Based on the insights gained in this investigation, a data analytics tool is currently being developed to identify factors and causes of poor performance, and ways to mitigate them.

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