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NV Energy Solar Integration Study: Cycling and Movements of Conventional Generators for Balancing Services

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July 2011

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Abstract

With an increasing penetration level of solar photovoltaic (PV) generation in the southern Nevada power system, the impact of solar on system operations needs to be carefully studied from mainly two perspectives: energy production and balancing services. On the energy production side, more startups and lower capacity factors on the conventional generators are anticipated, which can be quantified using production cost model simulations. On the balancing services side, it is expected that the balancing requirements to compensate for solar power variability will be larger in magnitude; meanwhile, generators providing load following and regulation services may also need to move up or down more frequently. This study develops two effective metrics to quantitatively evaluate the cycling and movements of conventional generators for providing balancing services at different levels of solar power penetration. The two metrics include (1) mileage and number of direction changes in balancing service (load following/regulation); and (2) ramp (or half-cycle) analysis. The results demonstrate a significant impact of increased solar capacity on balancing service provided by conventional generator movements. Busy hours of balancing requirements are also identified for different study cases, representing various solar penetration levels. This study provides a basis for evaluating the wear and tear of the conventional generators in the solar integration process in the Nevada power system.

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1.0 Introduction

1.1 Background

With an increasing penetration level of solar photovoltaic (PV) generation in the form of both utility scale and distributed generation (DG) in the southern Nevada system, the impact of solar on system operations needs to be carefully studied from mainly two perspectives: energy production and balancing services. On the energy production side, more startups and lower capacity factors on the conventional generators are anticipated, which can be quantified using production cost model simulations. On the balancing services side, it is expected that the balancing requirements to compensate for solar power variability will be larger in magnitude; meanwhile, generators providing load following and regulation services may also need to move up or down more frequently. The focus of this report is to quantitatively evaluate the cycling and movements of conventional generators for providing balancing services at different solar power penetration levels.

1.2 Objectives

This study is aimed at developing effective methodologies for the evaluation of conventional generator cycling and movements at different levels of large PV and DG penetration. The focus is generators providing balancing services, including regulation and load following, to compensate for the variability of load and solar PV. Two metrics are established in the report. The results provide a basis for evaluating the wear and tear of the conventional generators in the solar integration process.

1.3 Structure of the Report

The report is organized as follows: Section 2 explains the two proposed metrics to quantify generator cycling and movements; Section 3 describes the study cases including data requirements for different study scenarios; Section 4 shows the evaluation results; and Section 5 concludes the report.

2.0 Proposed Methodologies

There are two metrics defined in this section, which includes (1) mileage and direction changes of balancing requirements (including load following and regulation) and (2) a three-dimensional histogram (ramp rate, ramp duration and occurring frequency) of load following/regulation half-cycles. Each of these metrics is described below.

2.1 Mileage of Generator Movements for Regulation and Load Following

The first metric is to compute total mileage travelled in MW and total number of direction changes that conventional generators need to do to balance the variable load and solar. This idea is illustrated in Figure 2-1, where the swinging door algorithm is applied to smooth the curve and identify the turning points. With the identified turning points on the balancing curve like load following requirement,

Total mileage of moving up = sum of all moving up curves (projection on the y axis)
Total mileage of moving down = sum of all moving down curves (projection on the y axis)
Total number of direction changes = number of turning points on the curve

Such computation will be performed for each operating hour throughout the entire study year. In this way, busy hours that require more balancing services and movements can be observed easily. For a particular period of time like a day or a month, the required mileage and number of direction changes can be accumulated for comparison between cases with different levels of solar penetration. An example of such comparison is given in Figure 2-2.

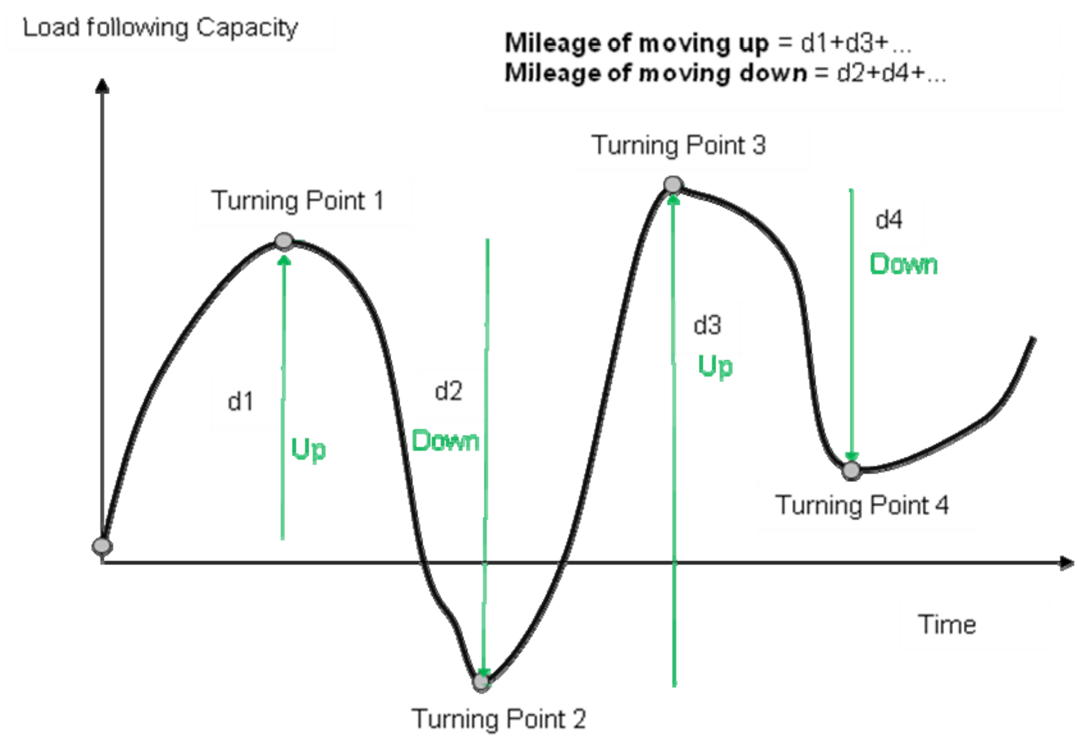

Figure 2-1. Computing generator movement mileage and number of direction changes

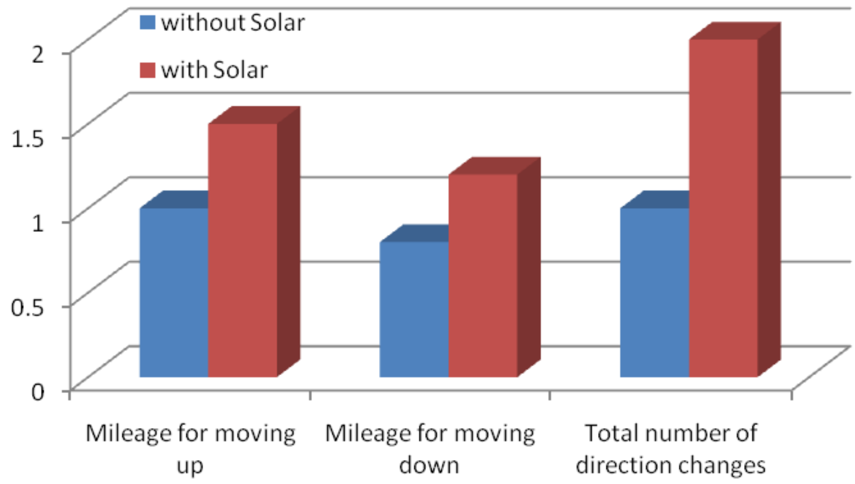

Figure 2-2. Comparison of mileage and number of direction changes between cases with and without solar

<u>Data requirements:</u>

1) Load following curves for different scenarios throughout the entire study year
2) Regulation curves for different scenarios throughout the entire study year

<u>Algorithm:</u>

1) Given a load following or regulation curve, apply the swinging door algorithm to smooth the curve
2) Identify the turning points in the curve throughout the year
3) For each operating hour,
    a. Compute mileage_up, mileage_down and number of direction change
    b. Compare different scenarios for 24 operating hours
4) Specify the time period to be studied, e.g., a day, a month or a year
    a. Sum up all mileage for moving up
    b. Sum up all mileage for moving down
    c. Sum up total number of direction changes
    d. Compare mileage up, mileage down and number of direction changes for all study scenarios.

2.2 Balancing Service Ramp Statistics

The second metric introduces the concept of half-cycle analysis, which can be used to evaluate and compare balancing requirements for different scenarios [1]. The idea of defining a half-cycle is similar to Metric 1 defined in Section 2.1. After identifying the turning points in load following/regulation curve, the magnitude between two adjacent turning points along the magnitude axis is defined as half-cycle magnitude (+/-). The distance between the two turning points along the time axis is the duration of each half-cycle, shown in Figure 2-3. Half-cycle ramp rate is then calculated as the ratio between half-cycle magnitude and half-cycle duration. A three-dimensional histogram with respect to duration and ramp rate can be generated for comparison, as shown in Figure 2-4.

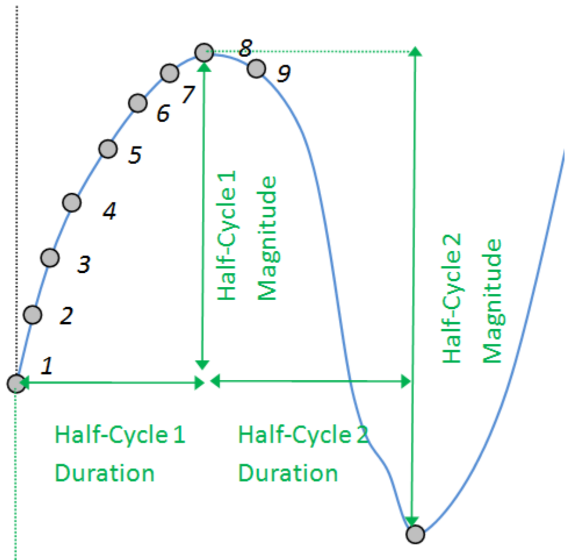

Figure 2-3. Concept of half-cycle analysis

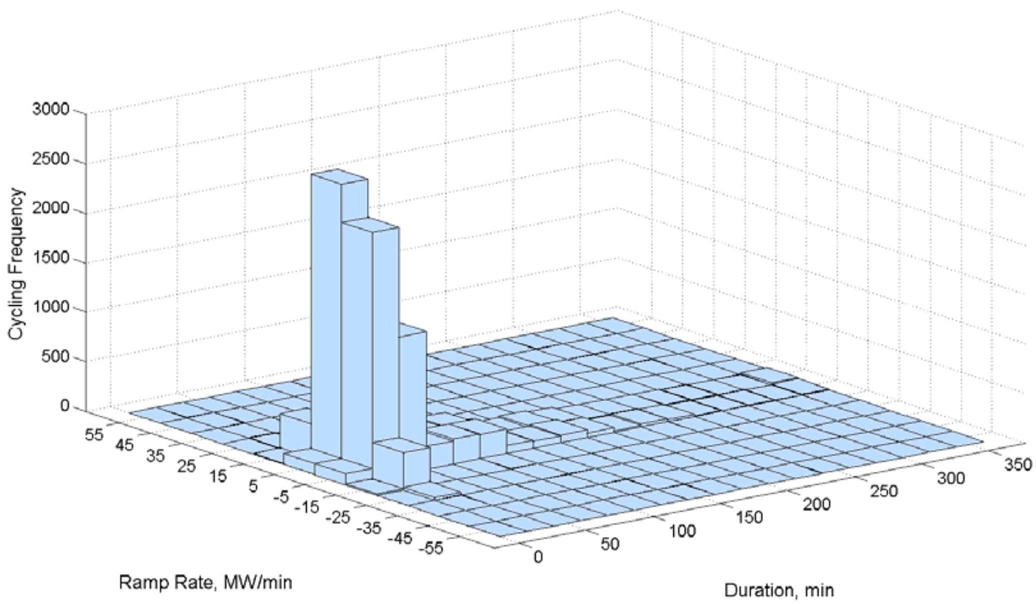

Figure 2-4. three-dimensional histogram for half cycles

<u>Data requirements:</u>

1) Load following curves for different scenarios throughout the entire study year
2) Regulation curves for different scenarios throughout the entire study year

<u>Algorithm:</u>

1) Given a load following/regulation curve, apply swinging door algorithm and identify turning points on the curve
2) Calculate half-cycle ramp rate and duration
3) Plot three-dimensional histograms for different scenarios using ramp rate and duration of half cycles

3.0 Study Scenarios

A total of 11 solar penetration cases were defined based on various combinations of large-scale PV and DG. The difference between these cases is summarized in Table 3-1.

Table 3-1. Definition of Study Cases

PV/DG Cases		**DG – Percent of Peak Load**			
		0 MW	**1% (50 MW)**	**9% (450 MW)**	**15% (750 MW)**
Large PV	**Case 0 – 0 MW**	Base Case			
	Case 1 – 149 MW	1	1A	1B	1C
	Case 2 – 222 MW		2A		
	Case 3 – 292 MW		3A		3C
	Case 4 – 492 MW		4A	4B	
	Case 5 – 892 MW		5A		

Base case is a southern Nevada system behavior without any large PV or DG installations. All other cases include certain amount of large PV and DG.

Generation schedules of 54 units for the entire study year are also provided by Navigant through PROMOD simulations. Load following and regulation curves are calculated using PNNL's method [2, 3]. These data form the basis for computing the above metrics.

4.0 Simulation Results and Discussions

This section discusses the simulation results obtained for the study cases defined in Section 3 using the proposed 2 metrics.

4.1 Mileage of Generator Movements for Regulation and Load Following

There are 10 cases studied in this section, including all cases defined in Table 3-1 but Case 1. Figure 4-1 compares the daily average mileages and direction changes required for load following in each operating hour, for Base Case and Case 5A. Figure 4-2 compares the same metrics but for regulation. Considering that generators do not need to move when load/generation mismatch is less than a certain threshold, regulation ramps with magnitudes less than 20 MW were not counted. From the results, busy hours including morning peak, afternoon peak and midnight peak with more frequent and larger generator movements can be identified. By comparing both cases, a large increase in load following mileage and number of direction changes is observed from 3:00 pm to 5:00 pm (Figure 4-1); a significant increase in mileage of regulation from 8:00 am to 5:00 pm is observed for Case 5A (Figure 4-2). The simulation results for the other cases are given in Appendix A.

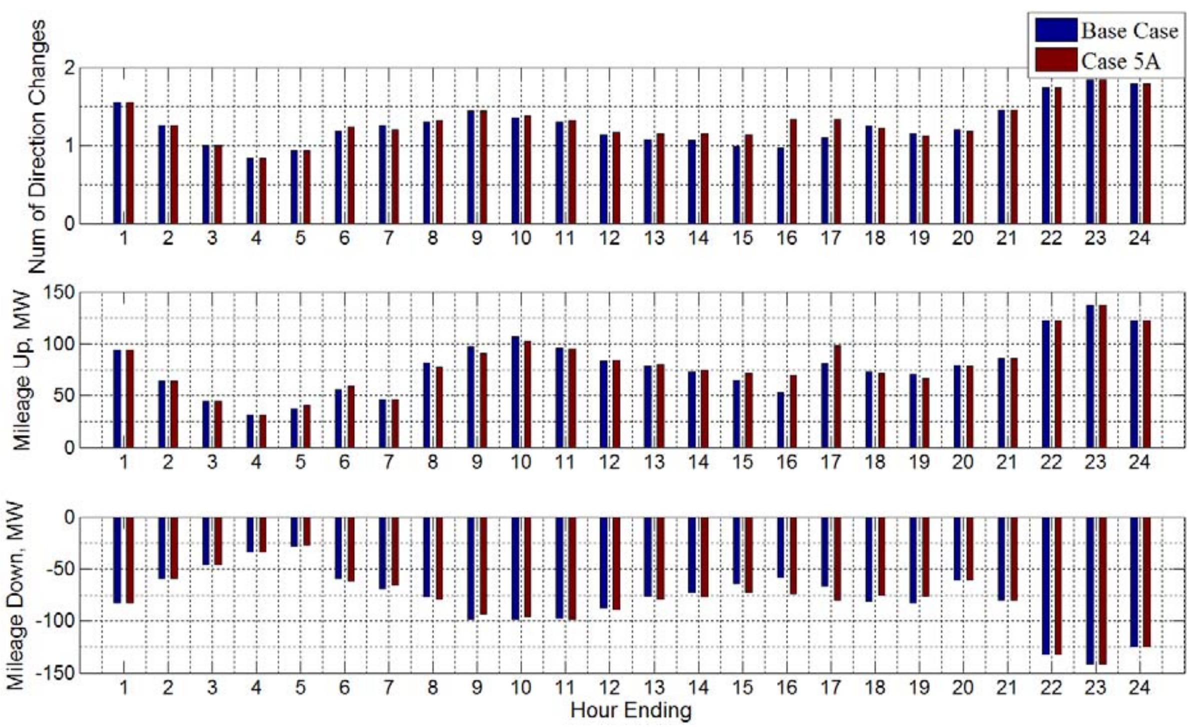

Figure 4-1. Daily average of direction changes and mileage for load following in Base Case and Case 5A

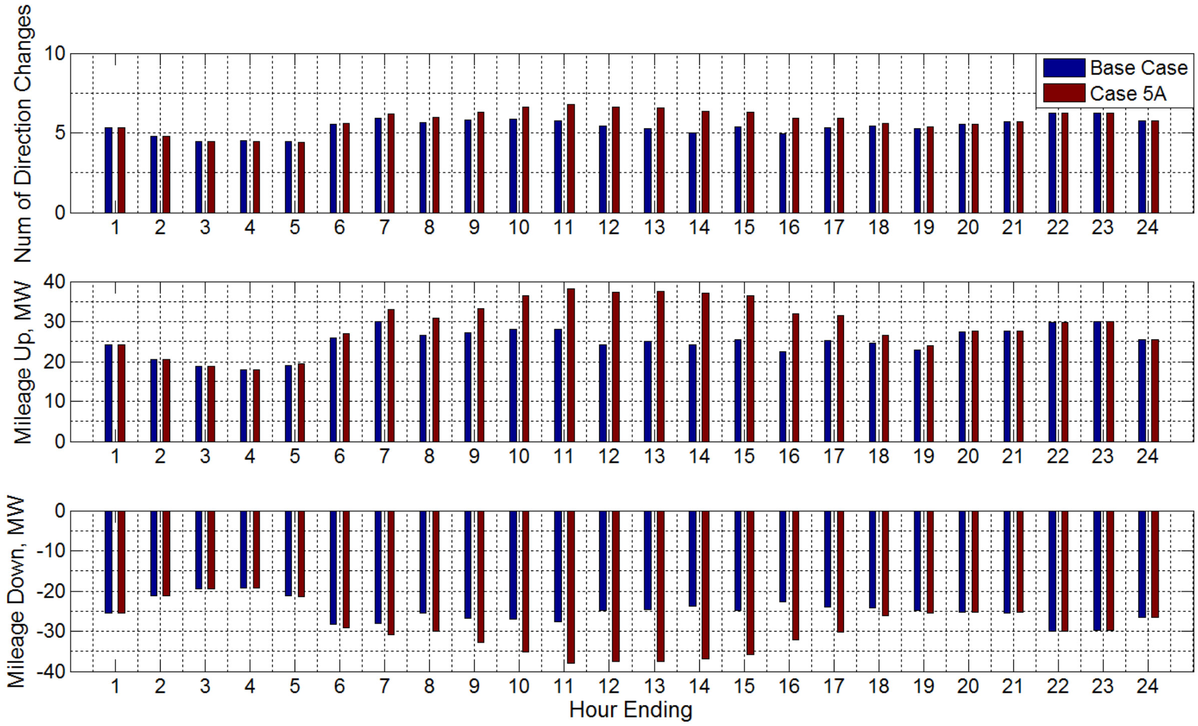

Figure 4-2. Daily average of direction changes and mileage for regulation in Base Case and Case 5A

Figure 4-3 and Figure 4-4 depict the trend of the yearly accumulated load following mileages and number of direction changes with respect to large-scale PV and DG capacity, respectively. Linear curve fitting using least square method is used to approximate the simulated points in each trend plot, and the derived linear equations are also shown in the figures. Although we observe certain nonlinear behavior in the plots, linear curve fitting method can provide a simple and direct approximation of the relationship between installed PV/DG and the movement of conventional generators. Nonlinear curve fitting method can also be used to derive a more accurate relationship if necessary.

The slope of the fitted linear curve can provide important information regarding additional wear and tear cost caused by increased capacity of large-scale PV or DG. For example, an increase of 1 MW in PV installed capacity can approximately cause 2.3 more direction changes and 240 MW of mileage increase (both up and down) in load following process throughout the year, as shown in the three subplots of Figure 4-3. Similarly, an increase of 1 MW in DG installed capacity can approximately cause 2.5 more direction changes and 300 MW of mileage increase (both up and down) in load following process, as shown in Figure 4-4. It is clearly shown that more large-scale PV and DG generation will cause more load following mileages and direction changes, indicating that conventional generators need to move more frequently to balance the variable resources.

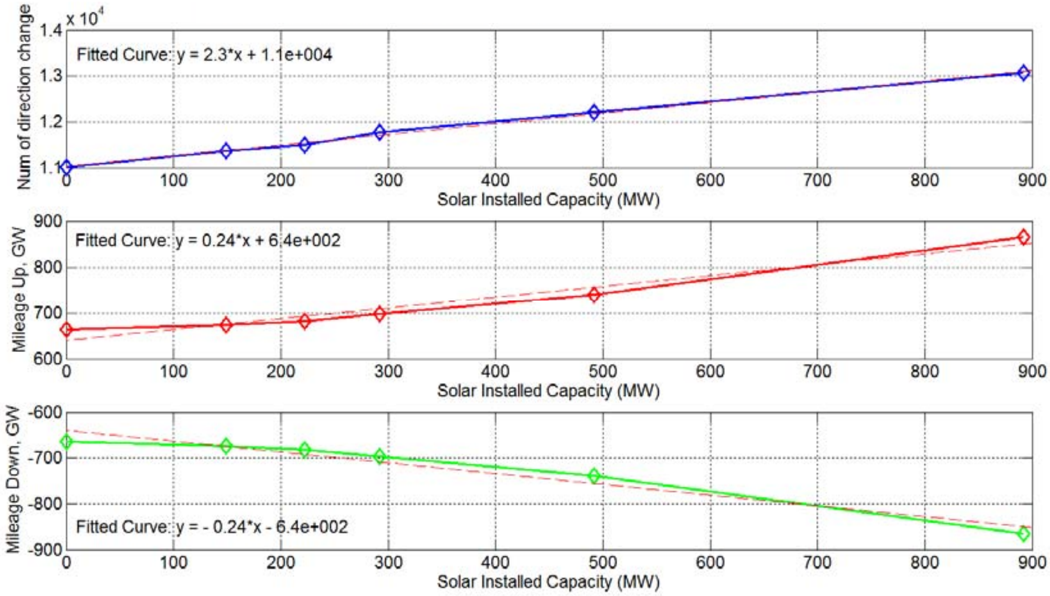

Figure 4-3. Comparison of yearly load following mileage and direction changes with regard to large-scale PV capacity (Study scenarios: Base Case, 1A, 2A, 3A, 4A, 5A)

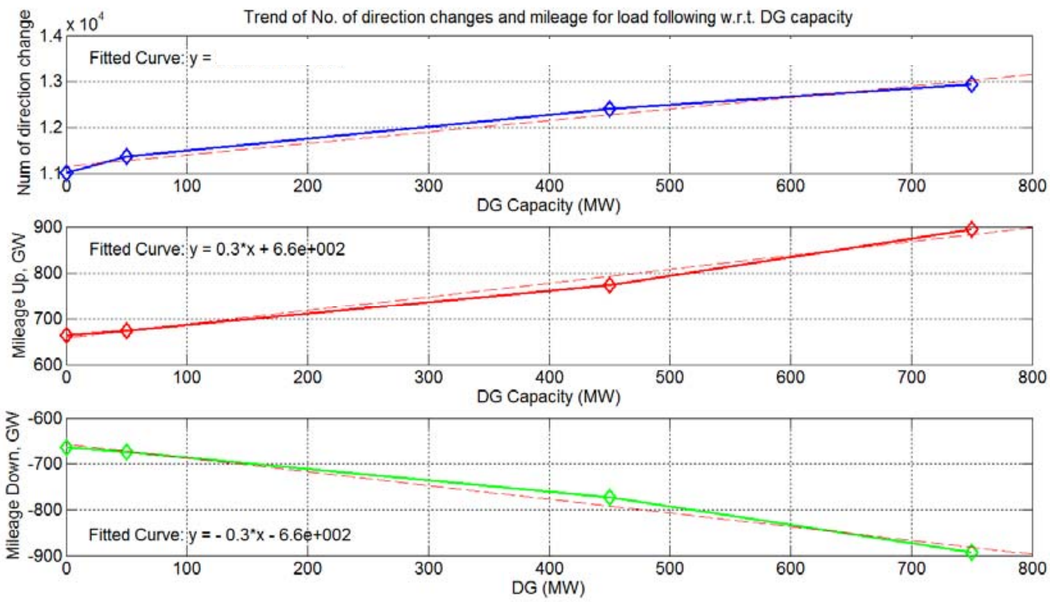

Figure 4-4. Comparison of yearly load following mileage and direction changes with regard to DG capacity (Study scenarios: Base Case, 1A, 1B, 1C)

Figure 4-5 and Figure 4-6 show the yearly accumulated regulation mileages and number of direction changes with respect to large PV and DG capacity, respectively. From Figure 4-5, an increase of 1 MW in PV installed capacity can cause 7.9 more direction changes and 170 MW of mileage increase (both up and down) in regulation process throughout a year. An increase of 1 MW in DG installed capacity can cause 8.5 more direction changes and 200 MW of mileage increase (both up and down) in regulation process (see Figure 4-6). Overall, both the accumulated mileage of regulation and total number of direction changes are increased as a result of the increasing PV or DG capacity.

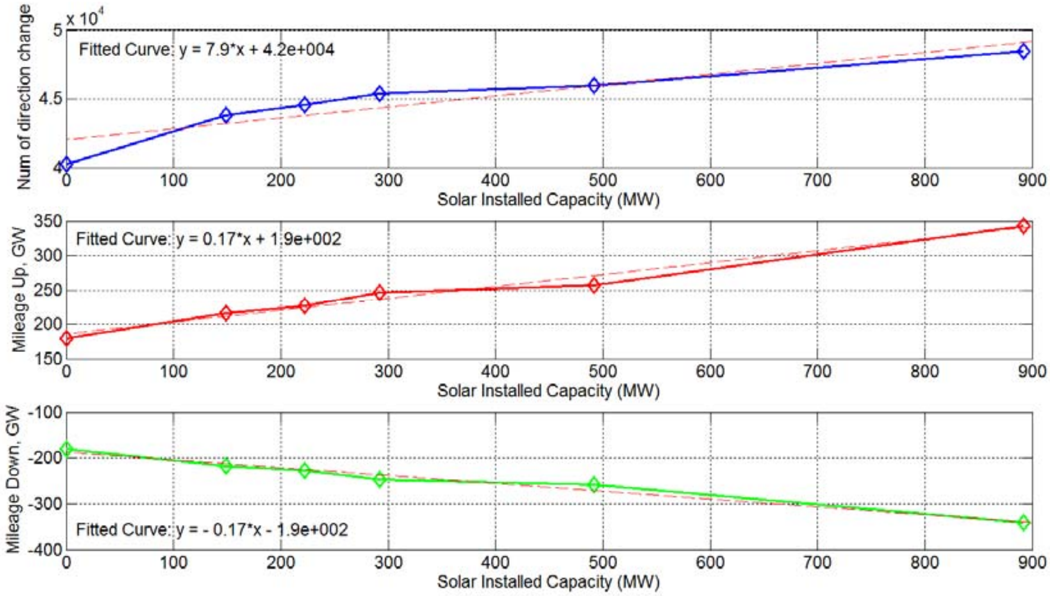

Figure 4-5. Comparison of yearly regulation mileage and direction changes with regard to large-scale PV capacity (Study scenarios: Base Case, 1A, 2A, 3A, 4A, 5A)

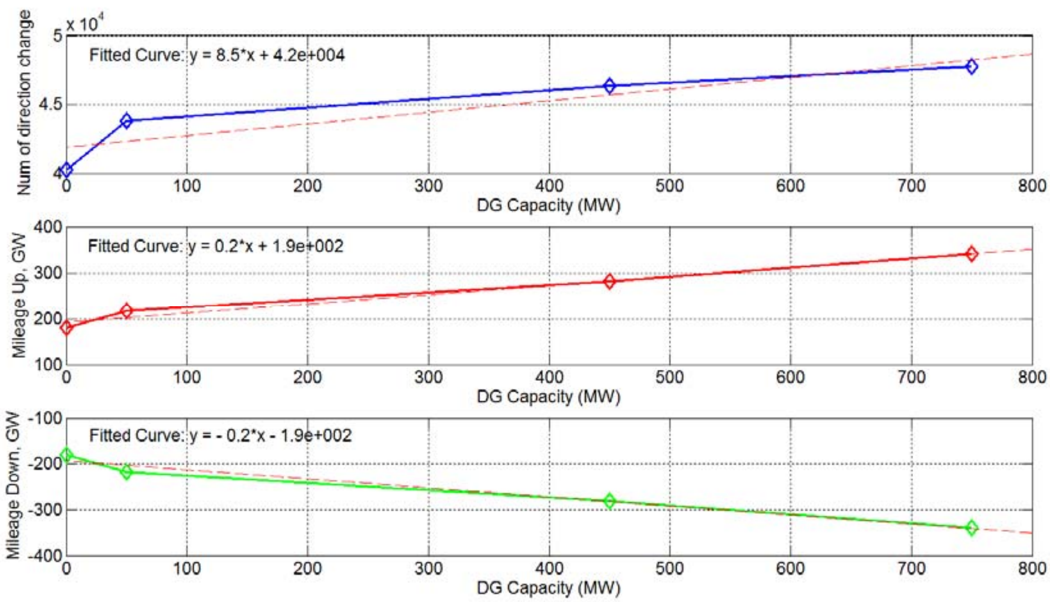

Figure 4-6. Comparison of yearly regulation mileage and direction changes with regard to DG capacity (Study scenarios: Base Case, 1A, 1B, 1C)

The trend plots are also generated for evaluating the solar impact on the generator movements during a single operating hour, 12 pm, as shown in Figure 4-7 through Figure 4-10. Similar trends of the number of direction changes and mileage in load following and regulation have been observed. For example, a 1 MW increase in PV capacity will cause 0.00043 times more direction changes and 0.027 MW/0.026 MW for moving up/down on a daily average for load following.

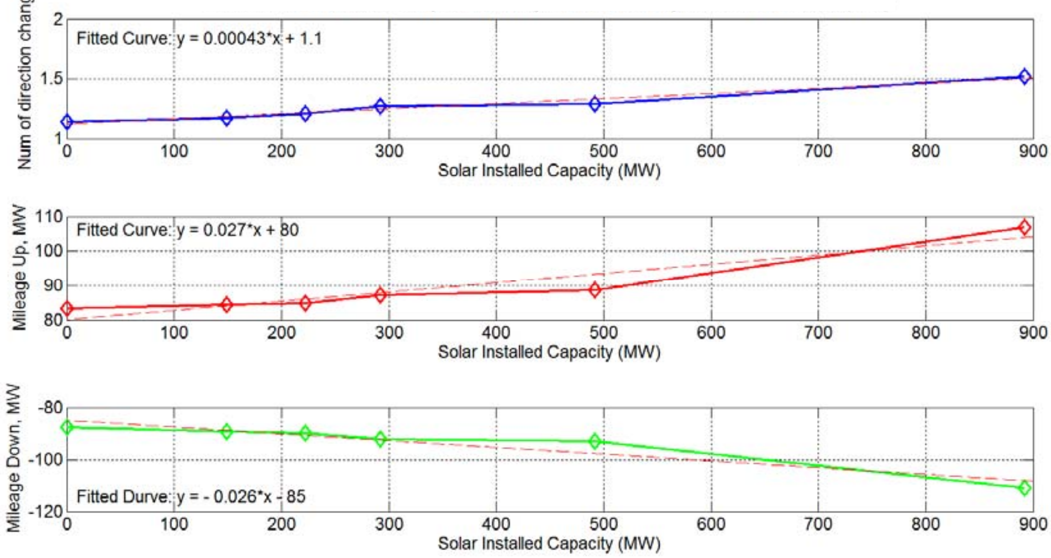

Figure 4-7. Comparison of average load following mileage and direction changes with regard to large-scale PV capacity for operating hour 12 pm (study scenarios: Base Case, 1A, 2A, 3A, 4A, 5A)

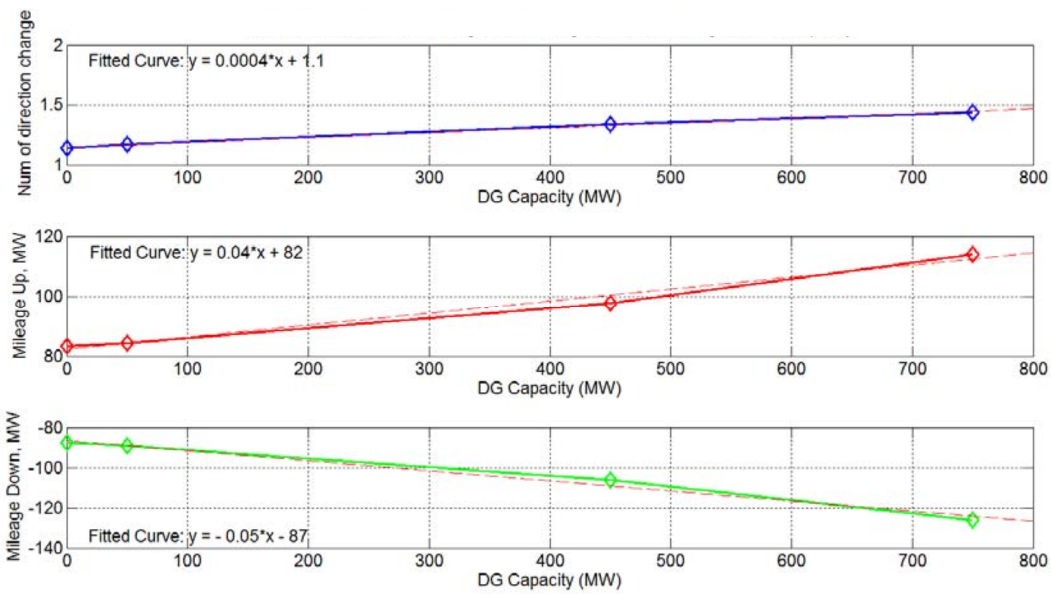

Figure 4-8. Comparison of average load following mileage and direction changes with regard to DG capacity for operating hour 12 pm (study scenarios: Base Case, 1A, 1B, 1C)

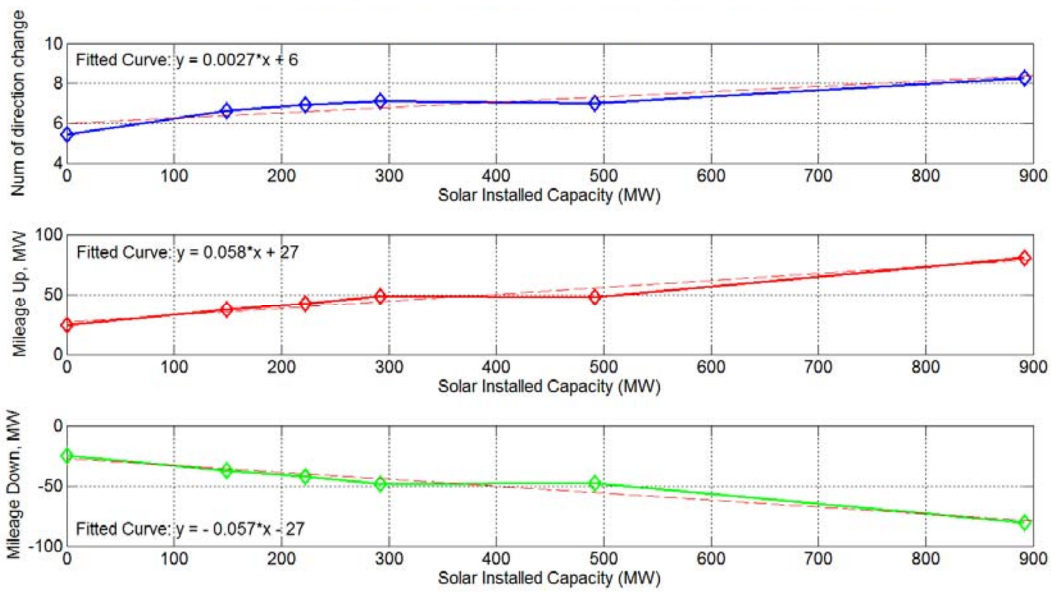

Figure 4-9. Comparison of average regulation mileage and direction changes with regard to large-scale PV capacity for operating hour 12 pm (study scenarios: Base Case, 1A, 2A, 3A, 4A, 5A)

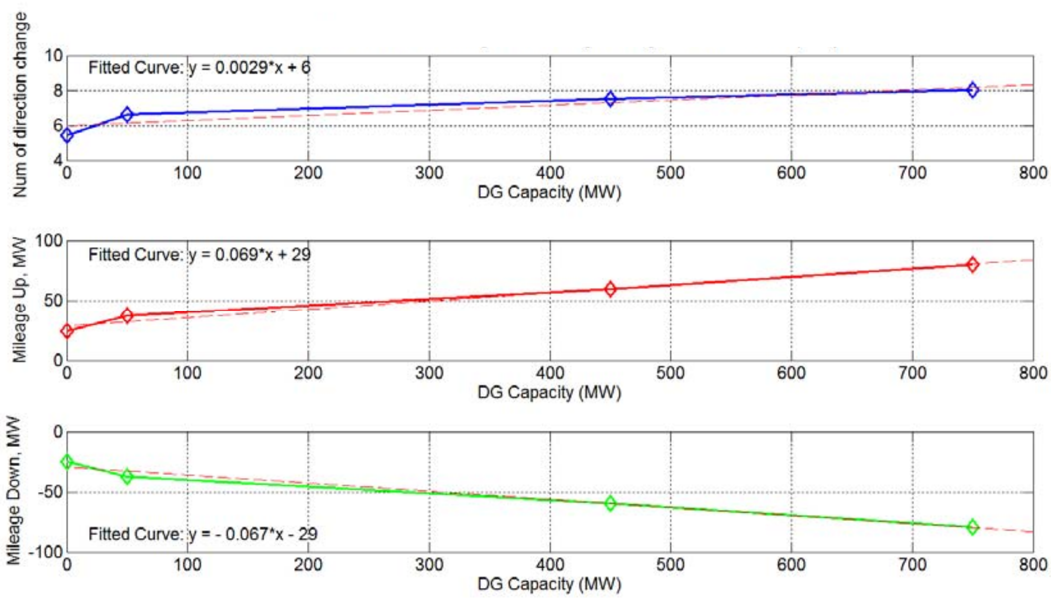

Figure 4-10. Comparison of average regulation mileage and direction changes with regard to DG capacity for operating hour 12 pm (study scenarios: Base Case, 1A, 1B, 1C)

To summarize, the proposed metrics can effectively demonstrate the impact of increased PV/DG capacity on the movements of conventional generators to provide load following and regulation services. In this study, regulation ramps with a magnitude lower than 20 MW were ignored to reflect the AGC deadband in the Nevada system. All the simulation results in this section have pointed out that increase in solar installed capacity (both large PV and DG) will require more movements from generators to provide additional balancing services. Linear curve fitting method is used to approximate the generator movements (number of direction changes, mileage up and mileage down) with respect to PV and DG installed capacity. The derived linear relationships are further summarized in Table 4-1. By comparing the slope of DG curves with that of PV curves, it can be concluded that the DG installed capacity in Nevada system has a larger impact than large-scale PV in increasing the total balancing services. That means, to install the same amount of solar in Nevada system, DG requires more balancing services than large-scale PV.

Table 4-1. Summary of linear fitted curves

Load following			
x\y	**Number of Direction Changes**	**Mileage Up (GW)**	**Mileage Down (GW)**
Large-scale PV (MW)	$y=2.3x+1.1*10^4$	$y=0.24x+6.4*10^2$	$y=-0.24x-6.4*10^2$
DG (MW)	$y=2.5x+1.1*10^4$	$y=0.3x+6.6*10^2$	$y=-0.3x-6.6*10^2$
Regulation			
x\y	**Number of Direction Changes**	**Mileage Up (GW)**	**Mileage Down (GW)**
Large-scale PV (MW)	$y=7.9x+4.2*10^4$	$y=0.17x+1.9*10^2$	$y=-0.17x-1.9*10^2$
DG (MW)	$y=8.5x+4.2*10^4$	$y=0.2x+1.9*10^2$	$y=-0.2x-1.9*10^2$

4.2 Ramp Statistics

Table 4-2 and Table 4-3 compare the load following half-cycle occurring frequency of Base Case and Case 5A; while Table 4-4 and Table 4-5 compare the regulation half-cycle occurring frequency of the same scenarios. As can be observed in these tables, more solar generation can cause higher frequency of load following movements. More regulation movements with higher ramp rate and longer duration are also observed. The obtained ramp statistics for the other study cases are shown in Appendix B.

Table 4-2. Load Following Half-cycle Analysis for Base Case

		Load following half-cycle ramp rate in MW/min											
Load following half-cycle duration in minutes	0	-55	-45	-35	-25	-15	-5	5	15	25	35	45	55
	10	0	0	0	0	14	112	110	8	0	0	0	0
	30	1	1	3	31	374	2496	2882	356	6	1	1	1
	50	0	0	0	0	0	1387	1159	0	0	0	0	0
	70	0	0	0	0	0	230	233	1	0	0	0	0
	90	0	0	0	0	0	249	197	0	0	0	0	0
	>=110	0	0	0	0	0	608	550	0	0	0	0	0

Table 4-3. Load Following Half-cycle Analysis for Case 5A

		Load following half-cycle ramp rate in MW/min											
Load following half-cycle duration in minutes	0	-55	-45	-35	-25	-15	-5	5	15	25	35	45	55
	10	0	0	0	0	78	504	384	56	0	0	0	0
	30	1	1	6	37	543	2706	3584	445	7	2	1	1
	50	0	0	0	0	9	1700	1235	18	0	0	0	0
	70	0	0	0	0	0	257	236	1	0	0	0	0
	90	0	0	0	0	0	238	188	1	0	0	0	0
	>=110	0	0	0	0	0	456	376	0	0	0	0	0

Table 4-4. Regulation Half-cycle Analysis for Base Case

Regulation half-cycle duration in minutes	Regulation half-cycle ramp rate in MW/min																	
0	-45	-40	-35	-30	-25	-20	-15	-10	-5	5	10	15	20	25	30	35	40	45
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	1	2	8	352	2261	2217	370	4	3	0	1	1	2	0
3	0	0	0	0	0	1	1	19	1331	1348	15	1	1	0	0	0	0	1
4	0	0	0	0	0	0	0	4	815	743	5	2	1	1	0	0	0	0
5	0	0	0	0	0	0	0	2	400	409	2	0	1	0	0	0	0	0
6	0	0	0	0	0	0	0	0	223	188	1	0	0	0	0	0	0	0
7	0	0	0	0	0	1	0	0	74	86	1	1	0	0	0	0	0	0
8	0	0	0	0	0	0	0	2	39	41	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	20	31	1	0	0	0	0	0	0	0
>=10	0	0	0	0	0	0	0	0	27	27	0	0	0	0	0	0	0	0

Table 4-5. Regulation Half-cycle Analysis for Case 5A

Regulation half-cycle duration in minutes	Regulation half-cycle ramp rate in MW/min																	
0	-45	-40	-35	-30	-25	-20	-15	-10	-5	5	10	15	20	25	30	35	40	45
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	2	1	1	6	8	38	579	2466	2422	608	31	9	2	1	4	2	1
3	0	2	1	0	6	16	46	212	1693	1747	207	51	13	5	2	3	3	3
4	1	1	1	4	7	16	37	148	1186	1137	170	27	22	8	1	2	1	1
5	0	0	0	4	4	19	26	108	867	855	107	32	22	8	5	0	0	0
6	0	0	0	4	5	10	31	79	566	556	78	22	11	7	2	1	0	0
7	0	0	0	0	2	6	16	54	385	345	60	20	7	2	0	0	0	0
8	0	0	0	1	1	3	12	37	272	279	48	10	4	1	1	0	0	0
9	0	0	0	0	0	3	8	25	189	201	31	5	3	0	0	0	0	0
>=10	0	0	0	0	1	1	8	35	470	447	29	4	0	0	0	0	0	0

Figure 4-11 through Figure 4-14 create trend plots of average half-cycle magnitude for load following/regulation with respect to large-scale PV and DG capacity, respectively. A 1MW increase in large-scale PV capacity can cause the average half-cycle magnitude of load following to increase 0.015 MW for both up and down directions; the same amount of increase in DG capacity can increase 0.023 MW in the average half-cycle magnitude of load following. Table 4-6 summarizes and compares the derived linear curves from Figure 4-11 to Figure 4-14. It is found that all of the average half-cycle magnitude curves (both positive and negative) are increased as a result of increased solar capacity, for both large-scale PV and DG. The impact of PV is larger than DG in causing more load following and regulation movements.

Table 4-6. Summary of linear fitted curves

Load following		
x\y	**Avg. Half-cycle Mag., Up (MW)**	**Avg. Half-cycle Mag., Down (MW)**
Large-scale PV (MW)	$y=0.015x+1.2*10^2$	$y=-0.015x-1.2*10^2$
DG (MW)	$y=0.023x+1.2*10^2$	$y=-0.023x-1.2*10^2$
Regulation		
x\y	**Mileage Up (GW)**	**Mileage Down (GW)**
Large-scale PV (MW)	y=0.0057x+9	y=-0.0056x-9
DG (MW)	y=0.0067x+9.2	y=-0.0066x-9.2

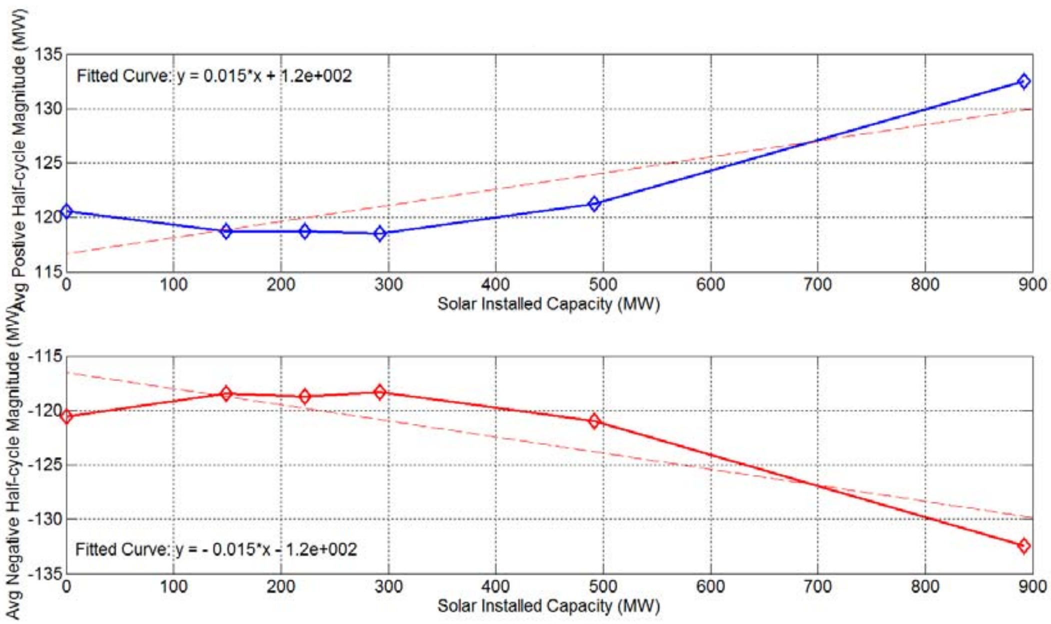

Figure 4-11. Comparison of average load following half-cycle magnitude with regard to large-scale PV capacity (Study scenarios: Base Case, 1A, 2A, 3A, 4A, 5A)

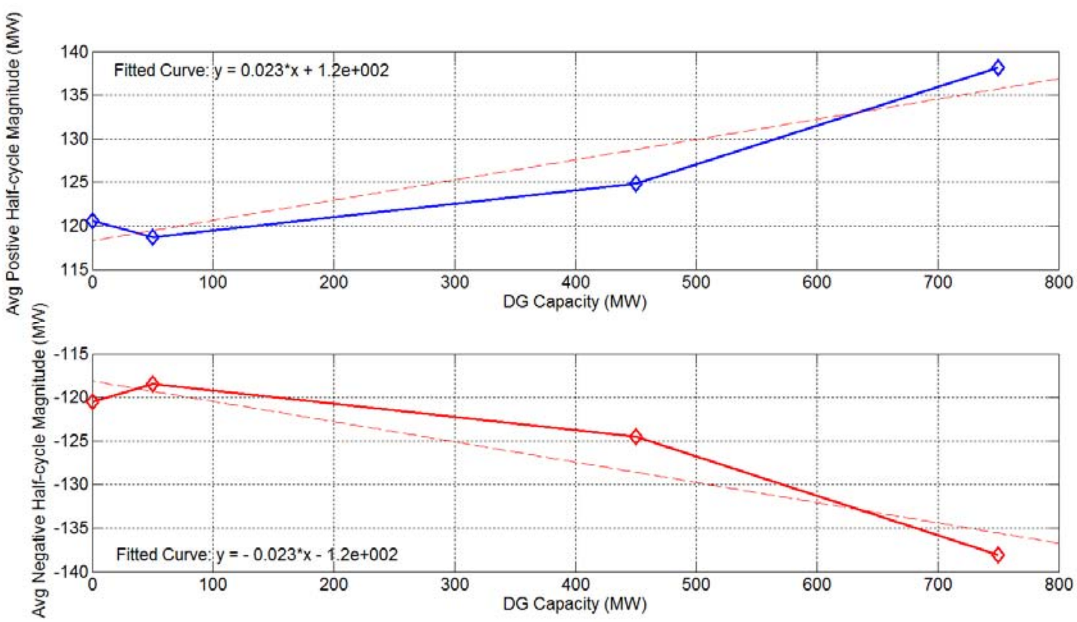

Figure 4-12. Comparison of average load following half-cycle magnitude with regard to DG capacity (Study scenarios: Base Case, 1A, 1B, 1C)

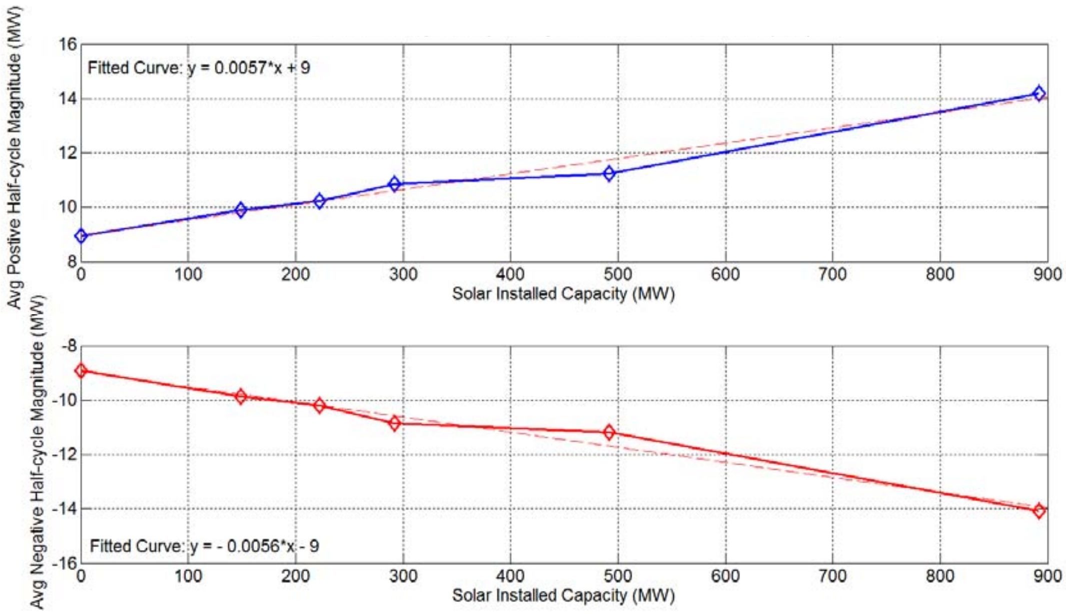

Figure 4-13. Comparison of average regulation half-cycle magnitude with regard to large-scale PV capacity (Study scenarios: Base Case, 1A, 2A, 3A, 4A, 5A)

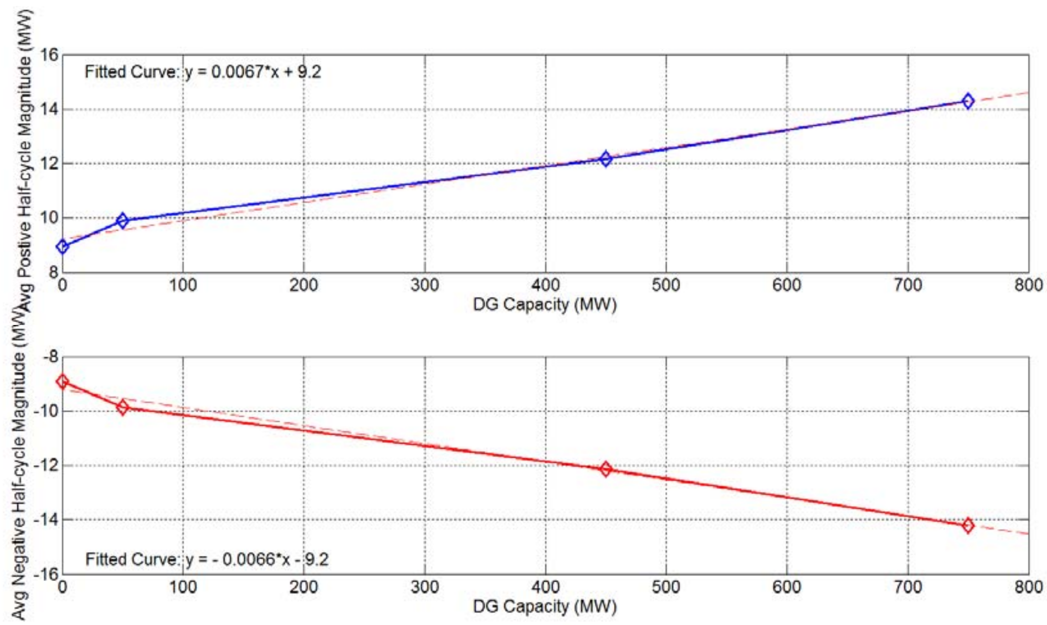

Figure 4-14. Comparison of average regulation half-cycle magnitude with regard to DG capacity (Study scenarios: Base Case, 1A, 1B, 1C)

5.0 Conclusions

This report develops two major metrics to evaluate the cycling and movements of conventional generators in the southern Nevada power system. The proposed metrics can effectively quantify the wear and tear on the conventional units for balancing the system. Metric 1 calculates the total mileage traveled in MW and number of direction changes to provide balancing services; and Metric 2 performs ramp/half-cycle analysis by generating three-dimensional histograms for load following or regulation ramps to evaluate the impact of large-scale PV and DG on the system. From the above analysis results, the following conclusions can be drawn:

(1) For load following, three busy periods are identified:
   a. 9:00 am ~ 11:00 am (the morning peak), valid for cases (Base, 1A, 2A, 3A)
   b. 15:00 pm ~ 17:00 pm (the afternoon peak), valid for cases (1A, 1B, 1C, 2A, 3A, 3C, 4A, 4B, 5A)
   c. 22:00 pm ~ 1:00 am (the midnight peak), valid for cases (Base, 1A, 1B, 1C, 2A, 3A, 3C, 4A, 4B)

(2) For regulation, no particular busy hours are observed for cases with little solar penetration (e.g., Base Case). For those cases with more solar power, the regulation busy hours focus on the period from 10:00 am to 16:00 pm (e.g. ,Cases 1C, 3A, 3C), when the solar irradiation is supposed to reach the maximum level.

(3) From Metric 2 results, it can be observed that higher penetration of large PV and DG can cause more high-ramp rate events with longer ramp duration, which poses larger ramp and capacity reserve requirements on conventional generators.

(4) Overall, a higher solar penetration will result in more direction changes on load following and regulation. Also, higher solar penetrations will lead to larger mileages, i.e., MW traveled by conventional generators to meet load following and regulation requirements.

This analysis provides a basis for the evaluation of generator cycling and movements for the integration of solar power. The metrics developed can be used to analyze generator wear and tear and associated maintenance cost if the cost data are available.

6.0 References

[1]. Y. V. Makarov, P. V. Etingov, N. Zhou, J. Ma, N.A. Samaan, R. Diao, S.V. Malhara, R.T. Guttromson, P. Du, and C. Sastry, 2010. "Analysis Methodology for Balancing Authority Cooperation in High Penetration of Variable Generation" PNNL-19229, Pacific Northwest National Laboratory, Richland, WA. [Online] Available: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-19229.pdf

[2]. Y.V. Makarov, S. Lu, B. McManus, J. Pease, 2008. "The Future Impact of Wind on BPA Power System Ancillary Services", *IEEE Transmission and Distribution Conference 2008*, Chicago, April 2008.

[3]. Y. V. Makarov, C. Loutan, J. Ma and P. de Mello, 2009. "Operational Impacts of Wind Generation on California Power Systems", IEEE Transactions on Power Systems, vol. 24, no. 2, pp. 1039-1050, May 2009.

APPENDIX A

Daily Average Mileage and Number of Direction Changes of Load Following and Regulation for Cases:

1A, 2A, 3A, 4A, 1B, 4B, 1C and 3C

Appendix A

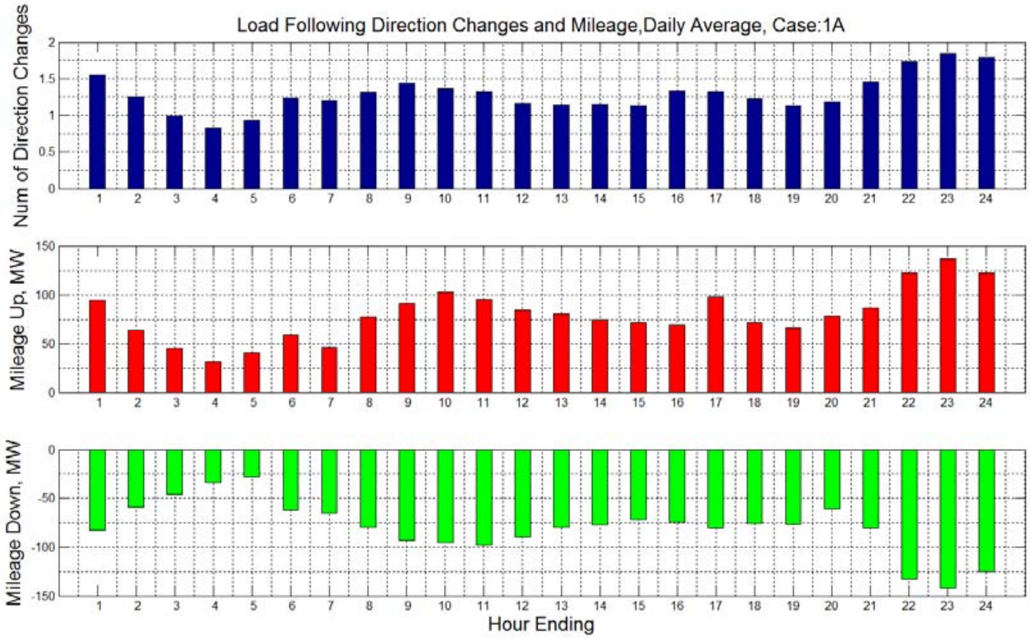

Figure A-1. Daily average of direction changes and mileage for load following in Case 1A

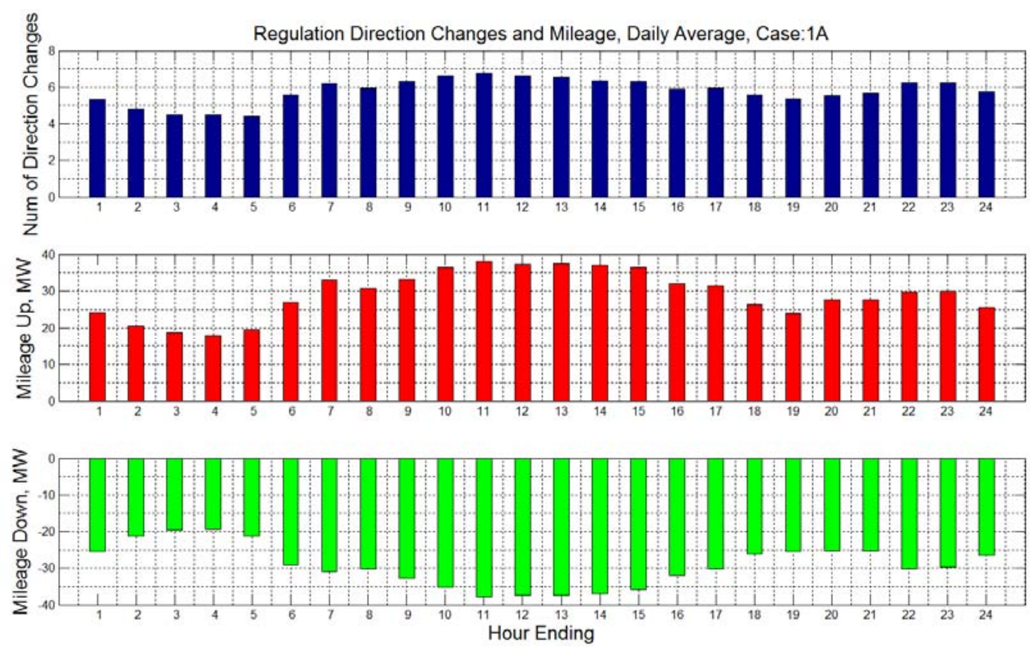

Figure A-2. Daily average of direction changes and mileage for regulation in Case 1A

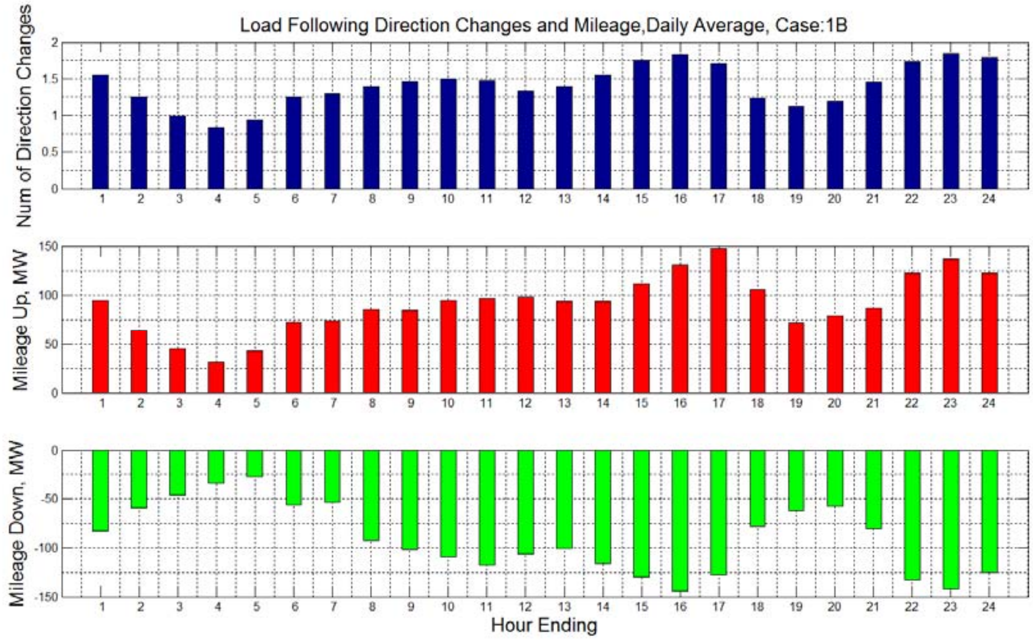

Figure A-3. Daily average of direction changes and mileage for load following in Case 1B

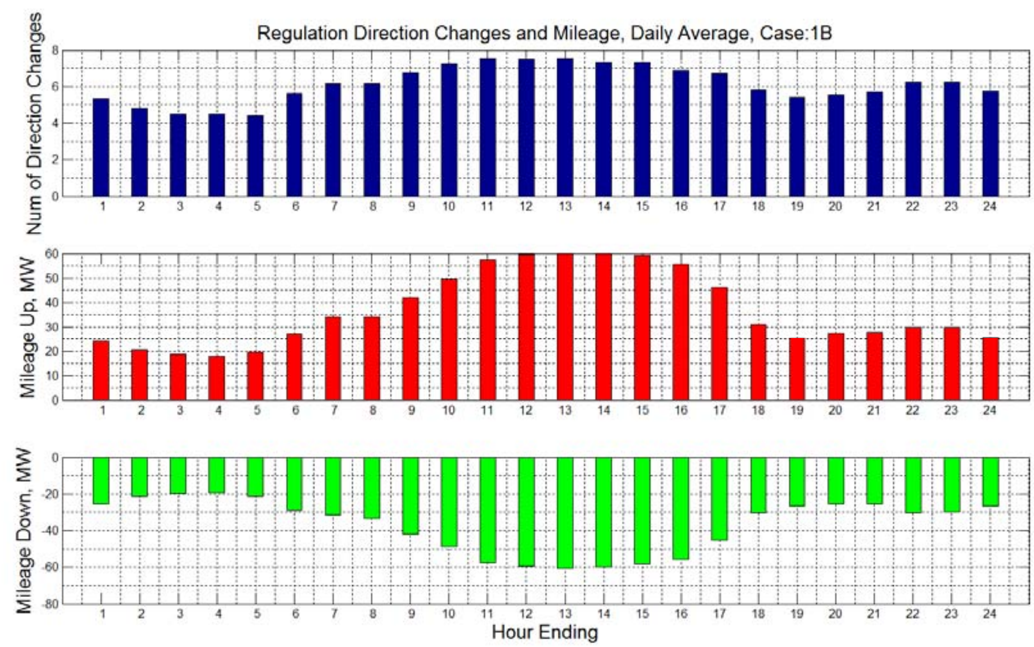

Figure A-4. Daily average of direction changes and mileage for regulation in Case 1B

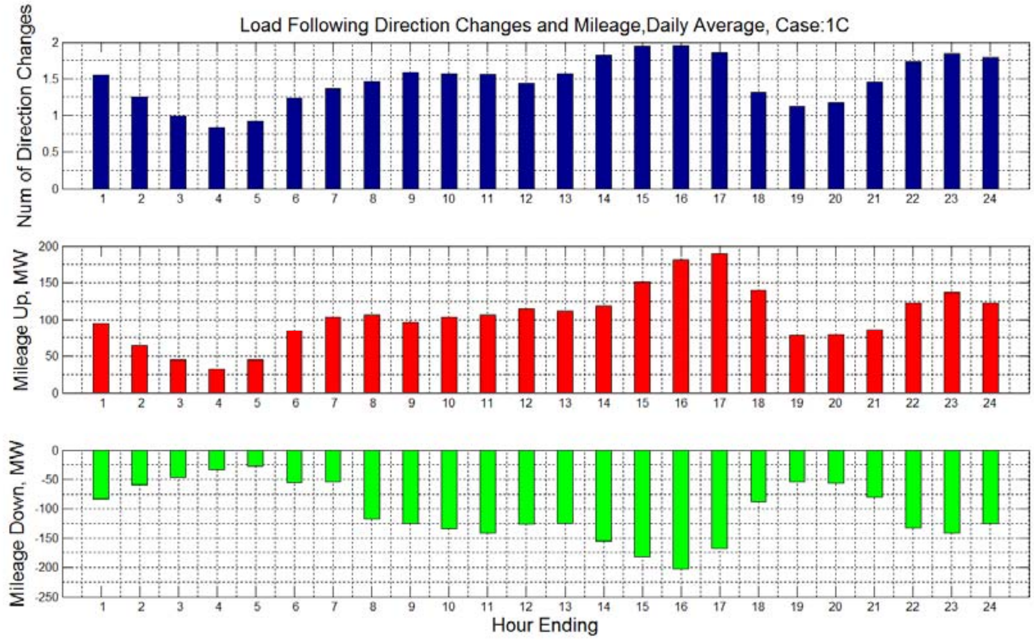

Figure A-5. Daily average of direction changes and mileage for load following in Case 1C

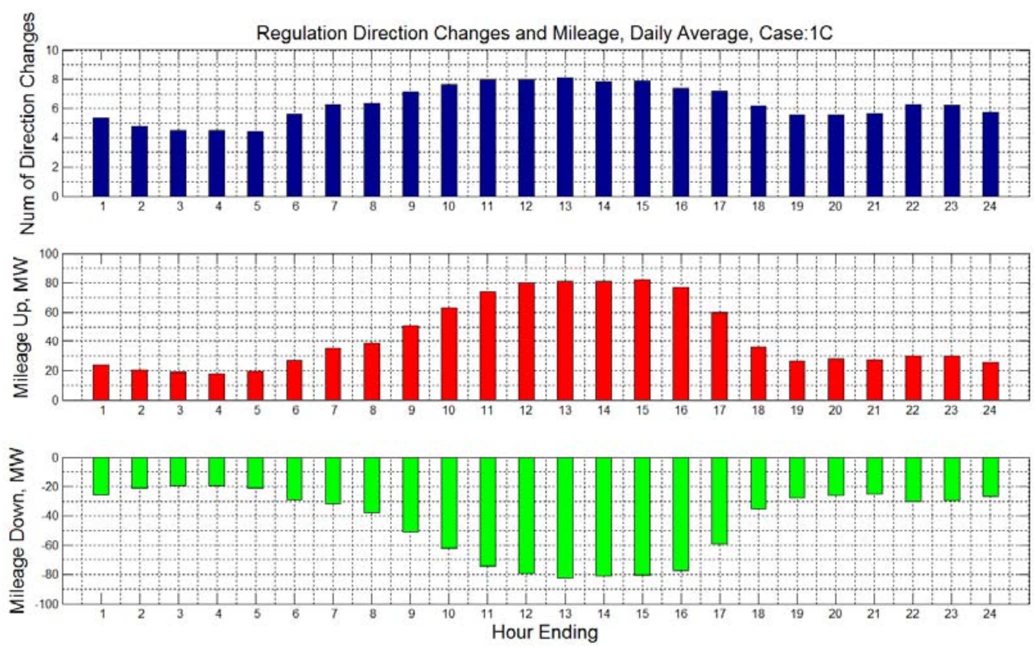

Figure A-6. Daily average of direction changes and mileage for regulation in Case 1C

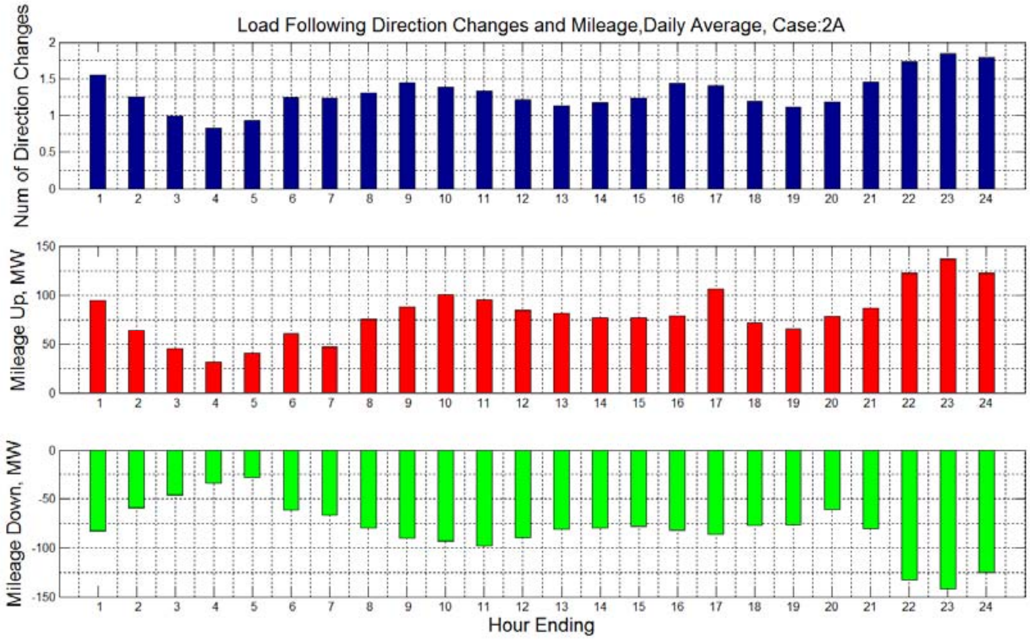

Figure A-7. Daily average of direction changes and mileage for load following in Case 2A

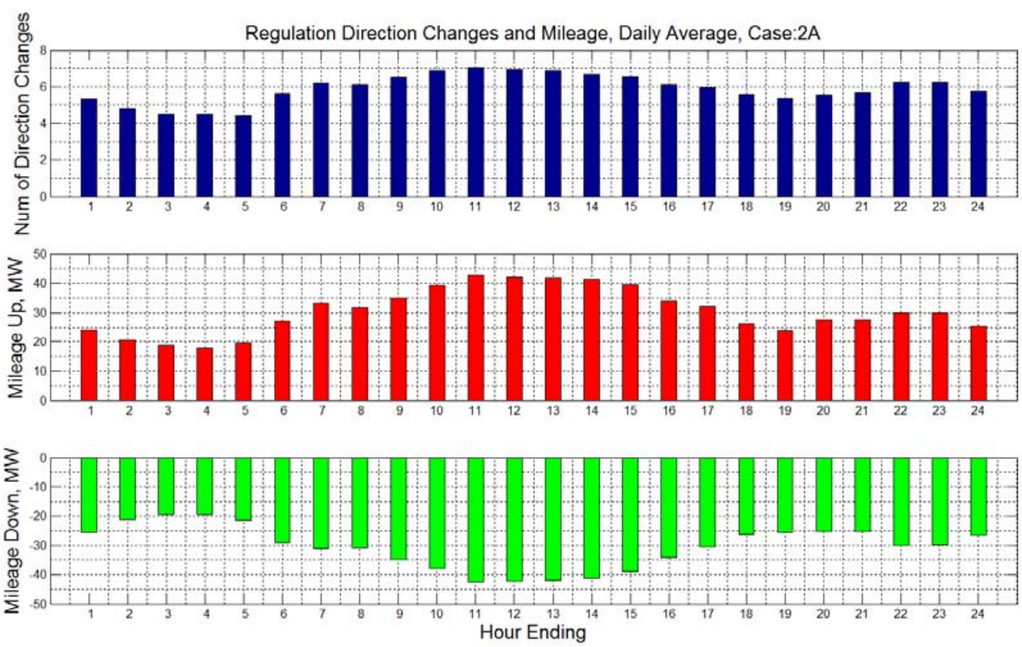

Figure A-8. Daily average of direction changes and mileage for regulation in Case 2A

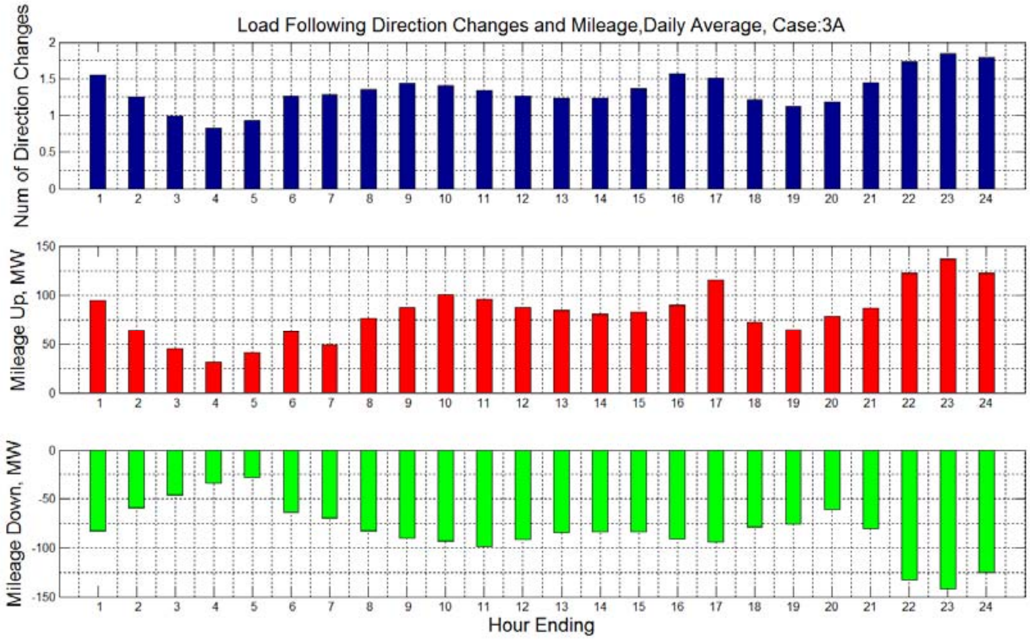

Figure A-9. Daily average of direction changes and mileage for load following in Case 3A

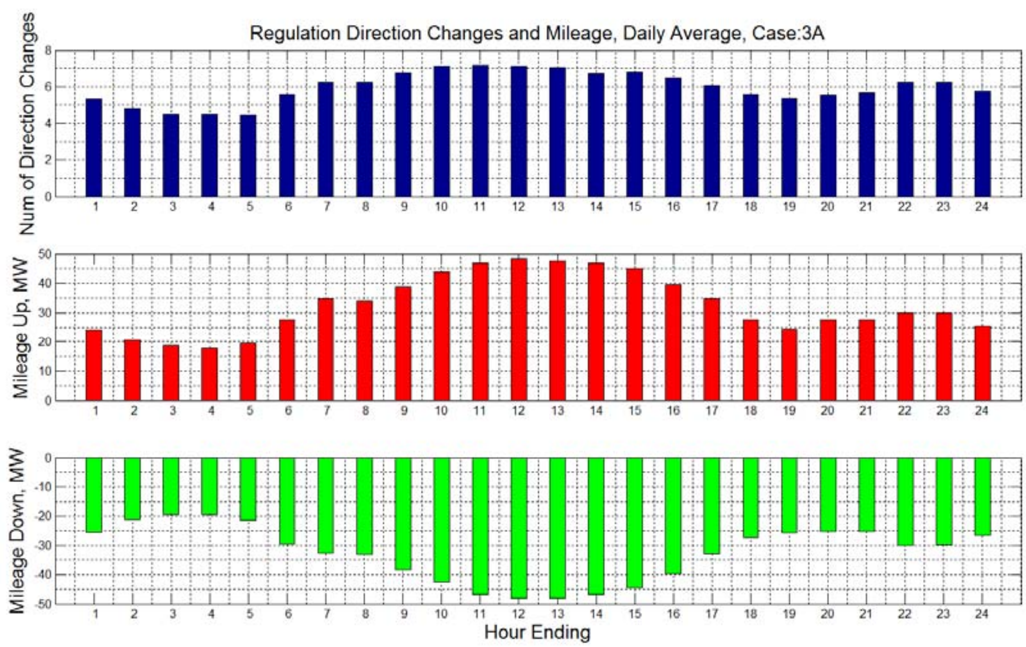

Figure A-10. Daily average of direction changes and mileage for regulation in Case 3A

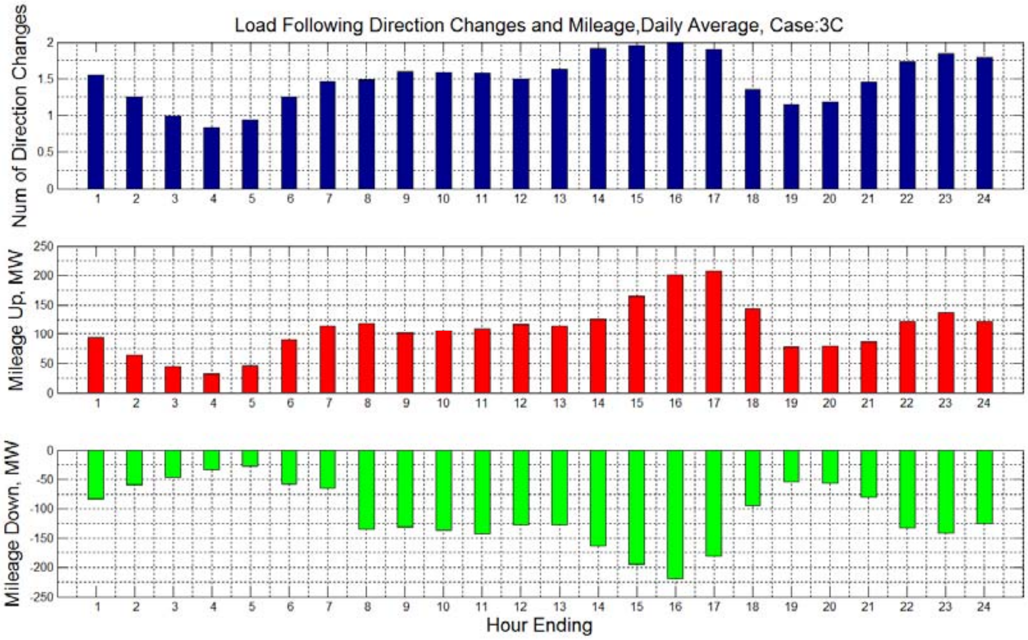

Figure A-11. Daily average of direction changes and mileage for load following in Case 3C

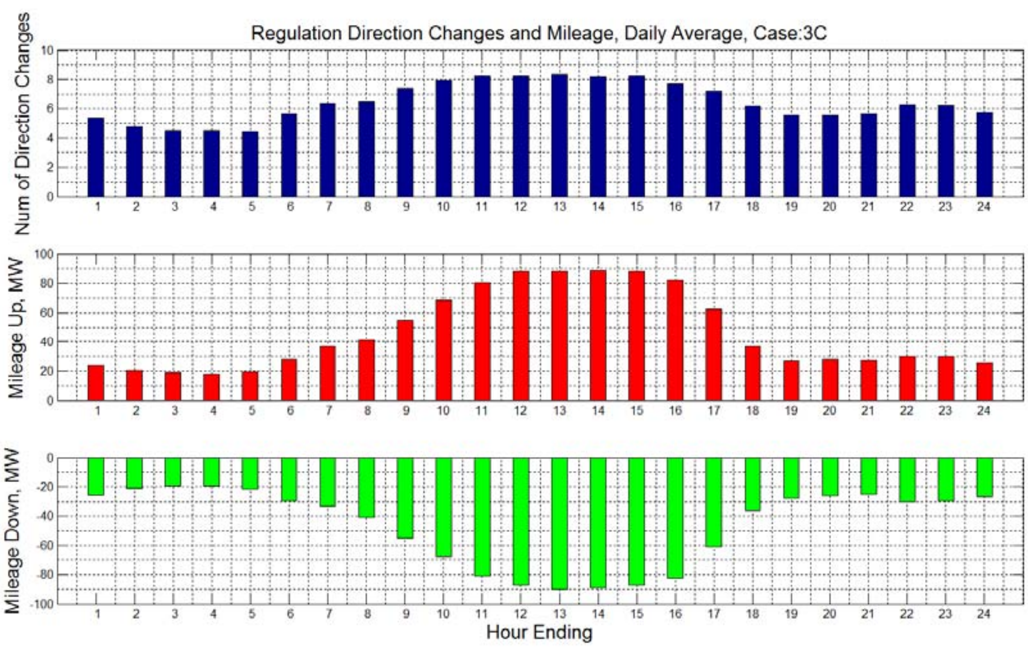

Figure A-12. Daily average of direction changes and mileage for regulation in Case 3C

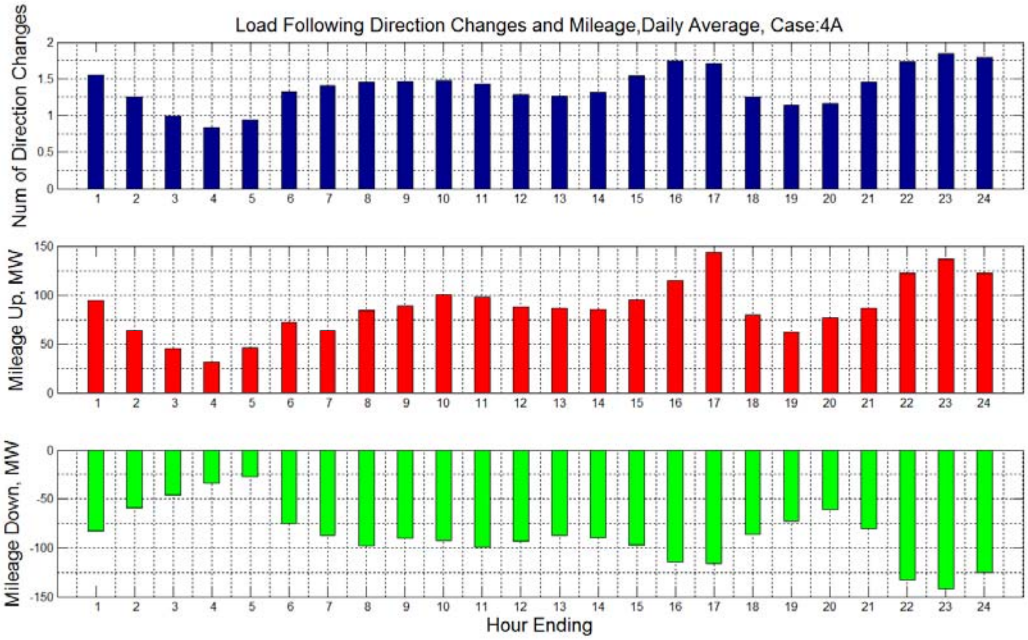

Figure A-13. Daily average of direction changes and mileage for load following in Case 4A

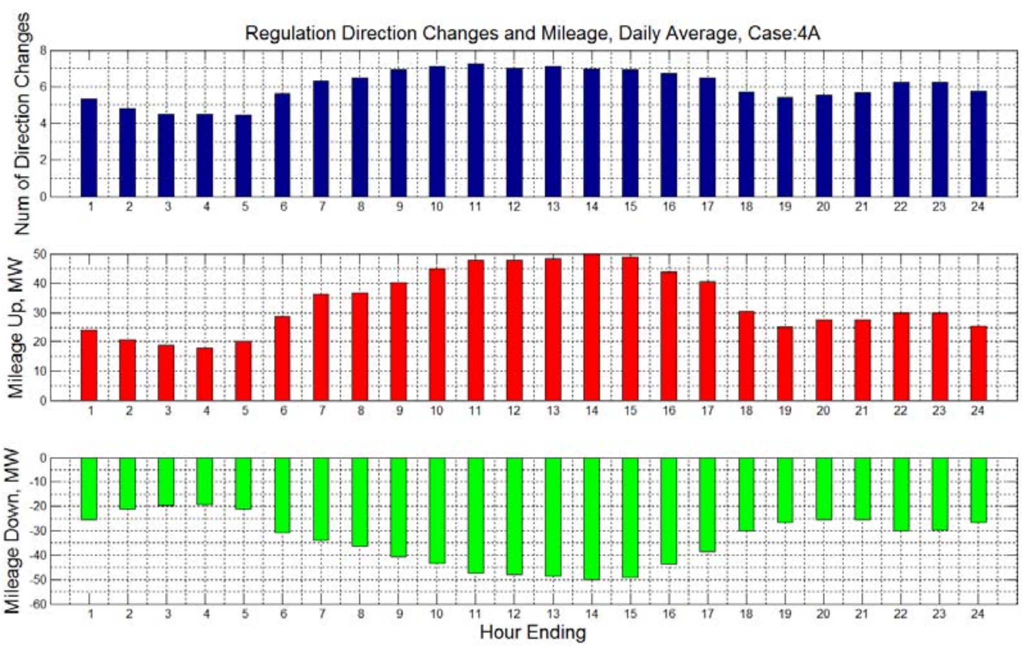

Figure A-14. Daily average of direction changes and mileage for regulation in Case 4A

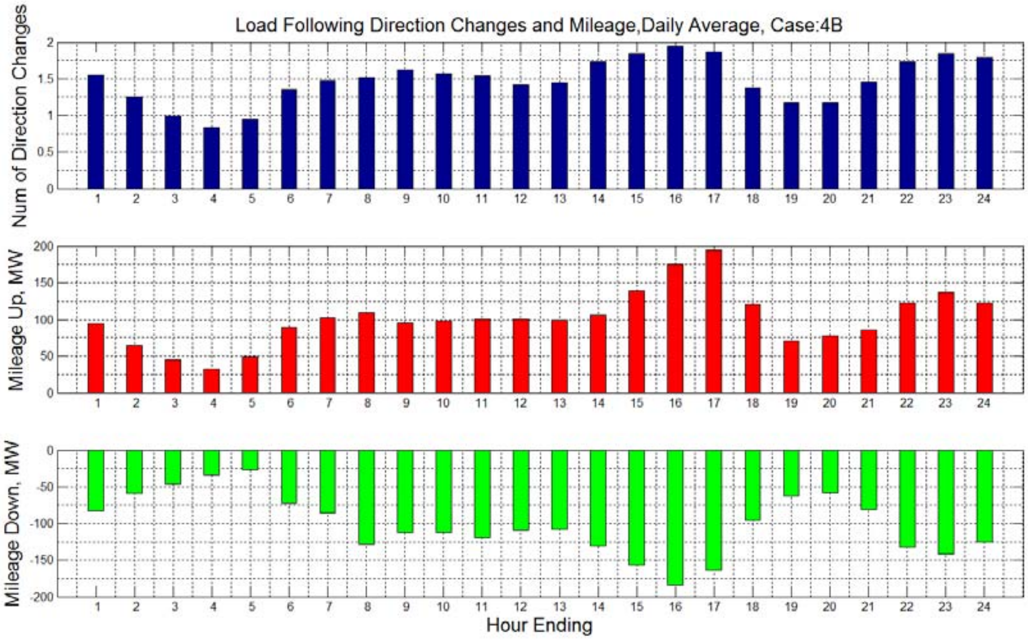

Figure A-15. Daily average of direction changes and mileage for load following in Case 4B

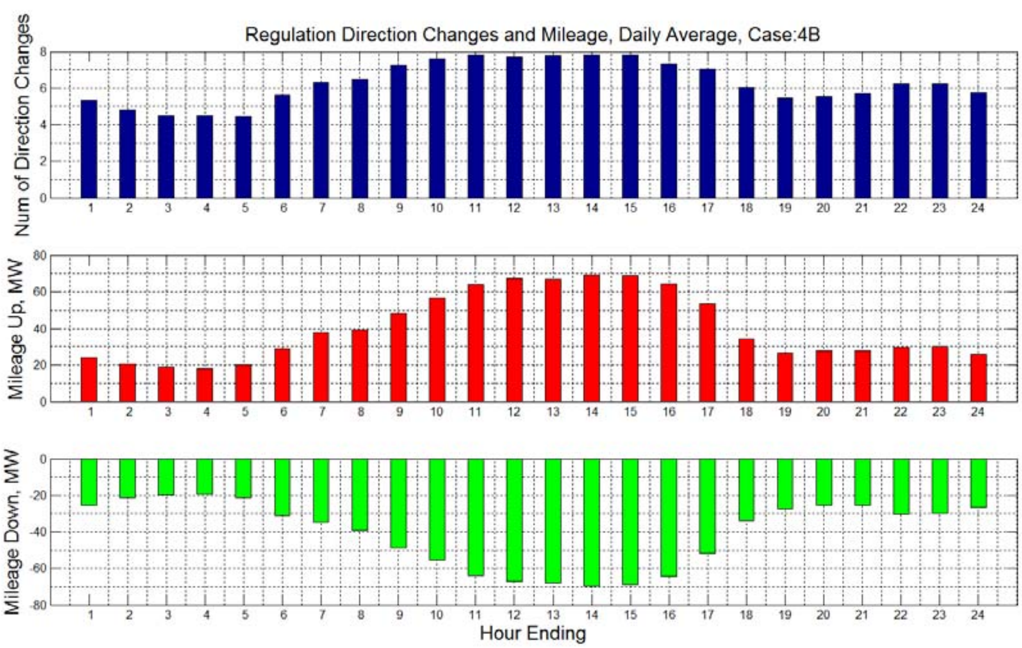

Figure A-16. Daily average of direction changes and mileage for regulation in Case 4B

APPENDIX B

Ramp Statistics of Load Following and Regulation for Cases: 1A, 2A, 3A, 4A, 1B, 4B, 1C and 3C

Appendix B

Table B-1. Load Following Half-cycle Analysis for Case 1A

		Load following half-cycle ramp rate in MW/min											
Load following half-cycle duration in minutes	0	-55	-45	-35	-25	-15	-5	5	15	25	35	45	55
	10	0	0	0	0	13	177	146	9	0	0	0	0
	30	1	1	4	31	385	2568	2971	345	6	1	1	1
	50	0	0	0	0	0	1445	1176	0	0	0	0	0
	70	0	0	0	0	0	259	246	0	0	0	0	0
	90	0	0	0	0	0	254	247	1	0	0	0	0
	>=110	0	0	0	0	0	548	527	0	0	0	0	0

Table B-2. Load Following Half-cycle Analysis for Case 2A

		Load following half-cycle ramp rate in MW/min											
Load following half-cycle duration in minutes	0	-55	-45	-35	-25	-15	-5	5	15	25	35	45	55
	10	0	0	0	0	12	200	162	7	0	0	0	0
	30	1	1	4	31	398	2576	3037	350	6	1	1	1
	50	0	0	0	0	0	1466	1160	0	0	0	0	0
	70	0	0	0	0	0	255	261	0	0	0	0	0
	90	0	0	0	0	0	250	235	1	0	0	0	0
	>=110	0	0	0	0	0	550	525	0	0	0	0	0

Table B-3. Load Following Half-cycle Analysis for Case 3A

		Load following half-cycle ramp rate in MW/min											
Load following half-cycle duration in minutes	0	-55	-45	-35	-25	-15	-5	5	15	25	35	45	55
	10	0	0	0	0	14	258	201	7	0	0	0	0
	30	1	1	5	31	393	2609	3113	348	6	1	1	1
	50	0	0	0	0	0	1551	1227	0	0	0	0	0
	70	0	0	0	0	0	249	265	0	0	0	0	0
	90	0	0	0	0	0	245	221	1	0	0	0	0
	>=110	0	0	0	0	0	528	488	0	0	0	0	0

Table B-4. Load Following Half-cycle Analysis for Case 4A

		Load following half-cycle ramp rate in MW/min											
Load following half-cycle duration in minutes	0	-55	-45	-35	-25	-15	-5	5	15	25	35	45	55
	10	0	0	0	0	38	320	226	14	0	0	0	0
	30	1	1	6	29	420	2709	3332	351	6	1	1	1
	50	0	0	0	0	0	1594	1234	0	0	0	0	0
	70	0	0	0	0	0	252	270	0	0	0	0	0
	90	0	0	0	0	0	250	222	1	0	0	0	0
	>=110	0	0	0	0	0	485	443	0	0	0	0	0

Table B-5. Load Following Half-cycle Analysis for Case 1B

		Load following half-cycle ramp rate in MW/min											
Load following half-cycle duration in minutes	0	-55	-45	-35	-25	-15	-5	5	15	25	35	45	55
	10	0	0	0	0	41	376	336	28	0	0	0	0
	30	1	1	8	33	481	2678	3276	368	6	1	1	1
	50	0	0	0	0	2	1632	1239	1	0	0	0	0
	70	0	0	0	0	0	225	303	0	0	0	0	0
	90	0	0	0	0	0	242	208	1	0	0	0	0
	>=110	0	0	0	0	0	487	431	0	0	0	0	0

Table B-6. Load Following Half-cycle Analysis for Case 4B

		Load following half-cycle ramp rate in MW/min											
Load following half-cycle duration in minutes	0	-55	-45	-35	-25	-15	-5	5	15	25	35	45	55
	10	0	0	0	2	77	467	387	40	0	0	0	0
	30	1	1	10	39	589	2655	3444	475	7	2	1	1
	50	0	0	0	0	4	1711	1267	18	0	0	0	0
	70	0	0	0	0	0	228	264	0	0	0	0	0
	90	0	0	0	0	0	230	189	1	0	0	0	0
	>=110	0	0	0	0	0	467	384	0	0	0	0	0

Table B-7. Load Following Half-cycle Analysis for Case 1C

		Load following half-cycle ramp rate in MW/min											
Load following half-cycle duration in minutes	0	-55	-45	-35	-25	-15	-5	5	15	25	35	45	55
	10	0	0	0	3	115	471	439	75	1	0	0	0
	30	1	2	9	48	617	2579	3385	482	12	2	1	1
	50	0	0	0	1	11	1678	1212	11	0	0	0	0
	70	0	0	0	0	2	215	278	3	0	0	0	0
	90	0	0	0	0	0	231	179	1	0	0	0	0
	>=110	0	0	0	0	0	485	387	1	0	0	0	0

Table B-8. Load Following Half-cycle Analysis for Case 3C

		Load following half-cycle ramp rate in MW/min											
Load following half-cycle duration in minutes	0	-55	-45	-35	-25	-15	-5	5	15	25	35	45	55
	10	0	0	0	5	131	500	445	93	2	0	0	0
	30	1	2	9	52	673	2520	3407	541	15	3	1	1
	50	0	0	0	0	11	1741	1210	23	0	0	0	0
	70	0	0	0	0	2	225	275	3	0	0	0	0
	90	0	0	0	0	0	219	184	0	0	0	0	0
	>=110	0	0	0	0	0	475	363	1	0	0	0	0

Table B-9. Regulation Half-cycle Analysis for Case 1A

Regulation half-cycle duration in minutes	Regulation half-cycle ramp rate in MW/min																	
0	-45	-40	-35	-30	-25	-20	-15	-10	-5	5	10	15	20	25	30	35	40	45
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	1	2	9	418	2364	2303	432	9	3	0	1	2	1	0
3	0	0	0	0	0	2	2	67	1502	1563	77	2	1	0	0	0	0	1
4	0	0	0	0	0	0	1	19	1034	982	26	2	0	1	0	0	0	0
5	0	0	0	0	0	1	0	6	561	578	5	0	1	0	0	0	0	0
6	0	0	0	0	0	0	0	0	337	334	1	0	0	0	0	0	0	0
7	0	0	0	0	0	1	0	0	179	180	1	1	0	0	0	0	0	0
8	0	0	0	0	0	0	0	2	95	94	1	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	55	63	1	0	0	0	0	0	0	0
>=10	0	0	0	0	0	0	0	0	72	74	0	0	0	0	0	0	0	0

Table B-10. Regulation Half-cycle Analysis for Case 2A

Regulation half-cycle duration in minutes	Regulation half-cycle ramp rate in MW/min																	
0	-45	-40	-35	-30	-25	-20	-15	-10	-5	5	10	15	20	25	30	35	40	45
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	1	2	10	436	2390	2288	448	10	3	0	1	2	1	0
3	0	0	0	0	0	2	4	94	1548	1612	86	2	1	0	0	0	0	1
4	0	0	0	0	0	0	1	23	1108	1023	30	4	0	1	0	0	0	0
5	0	0	0	0	0	0	1	11	643	640	10	0	1	0	0	0	0	0
6	0	0	0	0	0	0	0	0	374	353	5	0	0	0	0	0	0	0
7	0	0	0	0	0	1	0	0	196	222	2	1	0	0	0	0	0	0
8	0	0	0	0	0	0	0	2	113	121	1	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	83	77	1	0	0	0	0	0	0	0
>=10	0	0	0	0	0	0	0	0	93	80	1	0	0	0	0	0	0	0

Table B-11. Regulation Half-cycle Analysis for Case 3A

Regulation half-cycle duration in minutes	Regulation half-cycle ramp rate in MW/min																	
0	-45	-40	-35	-30	-25	-20	-15	-10	-5	5	10	15	20	25	30	35	40	45
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	2	2	17	439	2367	2294	471	16	3	0	1	2	1	0
3	0	0	0	0	1	5	14	120	1585	1632	110	27	3	2	0	0	0	1
4	0	0	0	0	0	1	5	70	1131	1042	59	8	0	1	0	0	0	0
5	0	0	0	0	0	1	2	38	679	678	28	3	1	0	0	0	0	0
6	0	0	0	0	0	0	0	8	425	409	19	1	0	0	0	0	0	0
7	0	0	0	0	0	1	0	8	248	275	8	1	0	0	0	0	0	0
8	0	0	0	0	0	0	0	7	174	149	7	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	2	98	108	5	0	0	0	0	0	0	0
>=10	0	0	0	0	0	0	0	2	156	145	1	0	0	0	0	0	0	0

Table B-12. Regulation Half-cycle Analysis for Case 4A

Regulation half-cycle duration in minutes	Regulation half-cycle ramp rate in MW/min																	
0	-45	-40	-35	-30	-25	-20	-15	-10	-5	5	10	15	20	25	30	35	40	45
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	1	4	14	464	2411	2340	494	12	5	0	1	2	1	0
3	0	0	0	0	0	1	9	104	1640	1666	121	12	3	0	0	0	0	1
4	0	0	0	0	0	2	8	57	1110	1072	63	7	1	1	0	0	0	0
5	0	0	0	0	0	0	5	29	742	733	49	3	1	0	0	0	0	0
6	0	0	0	0	0	0	3	15	471	414	22	2	0	0	0	0	0	0
7	0	0	0	0	0	1	1	8	276	313	13	2	0	0	0	0	0	0
8	0	0	0	0	0	0	0	4	192	173	4	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	3	118	123	4	1	0	0	0	0	0	0
>=10	0	0	0	0	0	0	0	3	195	196	3	0	0	0	0	0	0	0

Table B-13. Regulation Half-cycle Analysis for Case 1B

		Regulation half-cycle ramp rate in MW/min																	
Regulation half-cycle duration in minutes	0	-45	-40	-35	-30	-25	-20	-15	-10	-5	5	10	15	20	25	30	35	40	45
	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	2	4	16	475	2428	2416	478	17	5	2	1	2	1	0
	3	0	0	1	0	0	3	12	127	1579	1686	130	12	3	1	0	0	0	1
	4	0	0	0	0	0	3	10	74	1136	1068	79	13	2	1	0	0	0	0
	5	0	0	0	0	0	1	5	53	704	709	37	5	0	0	0	0	0	0
	6	0	0	0	0	0	1	8	42	472	439	24	2	0	0	0	0	0	0
	7	0	0	0	0	0	3	3	26	284	331	20	3	2	0	0	0	0	0
	8	0	0	0	0	0	0	4	22	223	211	29	5	0	0	0	0	0	0
	9	0	0	0	0	0	0	3	17	186	199	16	2	1	0	0	0	0	0
	>=10	0	0	0	0	0	0	0	20	404	387	37	2	0	0	0	0	0	0

Table B-14. Regulation Half-cycle Analysis for Case 4B

		Regulation half-cycle ramp rate in MW/min																	
Regulation half-cycle duration in minutes	0	-45	-40	-35	-30	-25	-20	-15	-10	-5	5	10	15	20	25	30	35	40	45
	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	2	1	6	15	528	2448	2389	547	21	8	1	1	2	1	0
	3	0	0	0	0	0	3	22	164	1675	1770	169	25	6	1	1	0	0	1
	4	0	0	0	0	1	3	18	113	1169	1138	114	23	2	1	0	0	0	0
	5	0	0	0	0	0	5	13	82	825	835	84	12	3	0	0	0	0	0
	6	0	0	0	0	0	1	9	61	563	502	49	8	0	0	0	0	0	0
	7	0	0	0	0	0	3	9	35	340	392	39	6	0	0	0	0	0	0
	8	0	0	0	0	0	1	4	24	280	260	34	10	0	0	0	0	0	0
	9	0	0	0	0	0	0	4	21	220	219	22	5	0	0	0	0	0	0
	>=10	0	0	0	0	0	0	4	29	480	463	38	5	0	0	0	0	0	0

Table B-15. Regulation Half-cycle Analysis for Case 1C

		Regulation half-cycle ramp rate in MW/min																	
Regulation half-cycle duration in minutes	0	-45	-40	-35	-30	-25	-20	-15	-10	-5	5	10	15	20	25	30	35	40	45
	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	2	0	0	1	2	7	25	555	2464	2429	558	34	9	2	1	3	2	0
	3	0	0	1	4	3	15	44	198	1613	1725	228	36	11	9	0	1	2	1
	4	0	0	0	3	2	15	37	129	1175	1096	120	42	13	7	1	0	0	0
	5	0	0	0	1	4	3	32	111	755	726	96	28	6	4	0	0	0	0
	6	0	0	0	0	2	6	24	74	516	498	70	13	3	4	0	1	0	0
	7	0	0	0	2	4	8	21	65	300	343	70	15	6	0	0	0	0	0
	8	0	0	0	0	2	4	7	35	227	251	59	17	6	2	0	0	0	0
	9	0	0	0	0	1	4	17	38	225	227	37	7	3	2	1	0	0	0
	>=10	0	0	0	0	1	3	19	85	510	485	86	32	4	2	0	0	0	0

Table B-16. Regulation Half-cycle Analysis for Case 3C

		Regulation half-cycle ramp rate in MW/min																	
Regulation half-cycle duration in minutes	0	-45	-40	-35	-30	-25	-20	-15	-10	-5	5	10	15	20	25	30	35	40	45
	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	2	0	0	2	3	9	29	598	2480	2436	607	39	8	3	1	3	1	0
	3	0	0	1	3	5	15	50	227	1675	1719	252	48	15	6	4	1	0	1
	4	0	0	0	3	4	18	43	170	1240	1132	181	43	21	4	2	1	0	0
	5	0	0	0	2	2	13	37	136	820	781	114	28	9	5	1	0	0	0
	6	0	0	0	0	2	13	21	84	541	545	92	20	4	3	0	0	0	0
	7	0	0	0	3	2	9	17	67	375	422	79	14	4	0	0	0	0	0
	8	0	0	0	0	1	4	15	52	283	297	64	18	11	1	0	0	0	0
	9	0	0	0	0	2	2	19	43	233	231	36	12	4	2	1	0	0	0
	>=10	0	0	0	0	1	3	18	83	552	528	81	32	5	3	0	0	0	0

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