THESIS

RELIABILITY QUANTIFICATION AND VISUALIZATION
FOR ELECTRIC MICROGRIDS

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ABSTRACT

RELIABILITY QUANTIFICATION AND VISUALIZATION FOR ELECTRIC MICROGRIDS

The electric grid in the United States is undergoing modernization from the state of an aging infrastructure of the past to a more robust and reliable power system of the future. The primary efforts in this direction have come from the federal government through the American Recovery and Reinvestment Act of 2009 (Recovery Act). This has provided the U.S. Department of Energy (DOE) with $4.5 billion to develop and implement programs through DOE's Office of Electricity Delivery and Energy Reliability (OE) over the a period of 5 years (2008-2012). This was initially a part of Title XIII of the Energy Independence and Security Act of 2007 (EISA) which was later modified by Recovery Act.

As a part of DOE's Smart Grid Programs, Smart Grid Investment Grants (SGIG), and Smart Grid Demonstration Projects (SGDP) were developed as two of the largest programs with federal grants of $3.4 billion and $600 million respectively. The Renewable and Distributed Systems Integration (RDSI) demonstration projects were launched in 2008 with the aim of reducing peak electricity demand by 15 percent at distribution feeders. Nine such projects were competitively selected located around the nation. The City of Fort Collins in co-operative partnership with other federal and commercial entities was identified to research, develop and demonstrate a 3.5MW integrated mix of heterogeneous distributed energy resources (DER) to reduce peak load on two feeders by 20-30 percent. This project was called FortZED RDSI and provided an opportunity to demonstrate integrated operation of group of assets including demand response (DR), as a single controllable entity which is often called a microgrid. As per IEEE Standard 1547.4-2011 (IEEE Guide for Design, Operation, and Integration of Distributed Resource Island

Systems with Electric Power Systems), a microgrid can be defined as an electric power system which has following characteristics:

(1) DR and load are present,

(2) has the ability to disconnect from and parallel with the area Electric Power Systems (EPS),

(3) includes the local EPS and may include portions of the area EPS, and

(4) is intentionally planned.

A more reliable electric power grid requires microgrids to operate in tandem with the EPS. The reliability can be quantified through various metrics for performance measure. This is done through North American Electric Reliability Corporation (NERC) metrics in North America. The microgrid differs significantly from the traditional EPS, especially at asset level due to heterogeneity in assets. Thus, the performance cannot be quantified by the same metrics as used for EPS. Some of the NERC metrics are calculated and interpreted in this work to quantify performance for a single asset and group of assets in a microgrid. Two more metrics are introduced for system level performance quantification. The next step is a better representation of the large amount of data generated by the microgrid. Visualization is one such form of representation which is explored in detail and a graphical user interface (GUI) is developed as a deliverable tool to the operator for informative decision making and planning. Supplementary documents provided with the electronic version of the thesis contain data and MATLAB© program codes for analysis and visualization for this work.

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DISCLAIMER

Portions of the work in Chapter 1 are derived from the reference [1.16], and portions in Chapter 2 are taken directly from the reference [2.1]. At the time of writing this thesis, a technical paper is also under preparation for submission to a peer reviewed conference proceedings that includes portions of Chapters 3 and 4 of this thesis. The author of this thesis is the first author for the work in above mentioned references. The co-authors of the above mentioned references are G.P. Duggan, R.T. Griffin, S. Suryanarayanan and D. Zimmerle from Colorado State University and M. Pool, S. Brunner from Brendle Group Inc.

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Chapter 1

Introduction

1.1 Objective

The main objective of this thesis is to describe some methodologies to quantify the performance of an existing microgrid using reliability metrics as per established criteria in the power industry and formulate new metrics to help the operator in better operation and planning of the microgrid. Data reduction and handling is explored in detail to treat excursions appropriately and retain maximum amount of data possible to gain more information. Another aspect of microgrid operation is addressed here which is the representation of information obtained from analysis of large amount of measurement data. This is done using various visualization methods for enhanced situational awareness of the operator.

1.2 Motivation

The electric grid in the United States is undergoing modernization from the state of an aging infrastructure of the past to a more robust and reliable power system of the future. The primary efforts in this direction have come from the federal government through the American Recovery and Reinvestment Act of 2009 (Recovery Act). This has provided the U.S. Department of Energy (DOE) with $4.5 billion to develop and implement programs through DOE’s Office of Electricity Delivery and Energy Reliability (OE) over the a period of 5 years (2008-2012). This was initially a part of Title XIII of the Energy Independence and Security Act of 2007 (EISA) which was later modified by Recovery Act. As a part of DOE’s Smart Grid Programs, the Smart Grid Investment Grants (SGIG), and the Smart Grid Demonstration Projects (SGDP) were developed as two of the largest programs with federal grants of $3.4 billion and $600 million respectively [1.1].

The Renewable and Distributed Systems Integration (RDSI) demonstration projects were launched by DOE in 2008 with the aim of reducing peak electricity demand by 15 percent at distribution feeders [1.2]. Nine such projects were competitively selected from around the nation. The City of Fort Collins in co-operative partnership with other federal, commercial and academic entities was identified to research, develop and demonstrate a 3.5MW integrated mix of heterogeneous distributed energy resources (DER) to reduce peak load on two feeders by 20-30 percent [1.2]. This project was called Fort Collins Zero Energy District FortZED RDSI and provided an opportunity to demonstrate integrated operation of group of assets including demand response (DR), as a single controllable entity which is often called a microgrid. As per IEEE Standard 1547.4-2011 (IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems), a microgrid can be defined as an electric power system which has following characteristics:

1.4.1 DR and load are present,

1.4.2 Has the ability to disconnect from and parallel with the area electric power systems (EPS),

1.4.3 Includes the local EPS and may include portions of the area EPS, and

1.4.4 Islanding is intentionally planned [1.3].

The reliability can be quantified through various metrics for performance measure. This is done through North American Electric Reliability Corporation (NERC) metrics in North America [1.4]. The microgrid differs significantly from the traditional EPS, especially at asset level due to heterogeneity in assets. Thus, the performance cannot be quantified by the same metrics as used for EPS. Data reduction, handling and analysis are explored in detail in this work. Excursions and bad data are treated to maximize accuracy and amount of information obtained from the data set. This forms a major portion of the thesis. Some of the NERC metrics are calculated and interpreted in this work to quantify performance for a single asset and group of assets in a microgrid. Two more metrics are introduced for system level performance quantification. The next step is a better representation of the large amount of data generated by the microgrid. Visualization is one such form of representation which is explored in detail and a graphical user interface (GUI) is developed as a deliverable tool to the operator for informative decision making and planning.

1.3 Scope

The scope of this thesis is to present results from existing methods and introduce newer methods to quantify the performance of a microgrid system. Reliability metrics are calculated for individual assets and for assets when grouped together. The techniques for data reduction and metric calculations are presented so that the metrics calculated using the present data set can be used to compare the performance to the assets in EPS. NERC metrics and their application to the assets in a microgrid are presented along with interpretation for each metric. Since, these values are calculated over past data and the sample size is of demonstration data used spans only a few hours, the metric values obtained may not provide a long term performance of the microgrid operation but the methods suggested can be applied to a larger data set to obtain more robust information for decision making. This work deals only with deterministic analysis of data, no probability models were formed using the data. Calculations were done based on interpretation of input variables in case of microgrids using NERC formulae for performance assessment.

The proposed metrics would aid in planning and designing a microgrid and are simple to use. The work done here is based on data already collected from the system, so it is posterior analysis. It does not provide or take into account optimum power flow or system stability. Calculations are made assuming that even deploying the full capacity of the microgrid, the system would remain stable and is always connected to the EPS. However, the FortZED RDSI demonstration case presented for metrics had the control system limiting the dispatch of no more than 500kW of net power in a single command. Visualization is provided for each metric and various combinations and comparisons can be done using the GUI. A few features and concepts are presented in a form that provides the flexibility of time resolution selection and data selection to enhance user interaction.

The concepts and methodologies presented here can be used as is or modified to fit into a present standard or help in formulation of a future standard for data visualization, data resolution for an operation, data handling and performance quantification. Most features of performance quantification and visualization can be fit easily into the paradigm of operation and planning of microgrids. The aspect of present state of microgrids is further explored in the next section.

1.4 Literature review

This section outlines the present state of work in the area of microgrids with relevant literature reviewed for the following: data reduction, performance metrics, and visualization.

1.4.1 Microgrids

As defined by IEEE Standard 1547.4-2011, a microgrid has some additional features of a power system that differentiates it from the EPS. Some of these features are due to the inherent characteristics of the assets forming the microgrid. Finite inertia, heterogeneity of assets, location of assets in the vicinity of the loads, and within the control territory of the distribution utility are some of these differentiating characteristics. A microgrid still appears as a single controllable entity to the EPS.

Microgrids can help in increasing reliability, enhance renewable energy penetration, dynamic islanding, and improve generation efficiency through waste heat recovery [1.5], [1.6]. Modern technologies such as low cost power electronics with faster switching times, and advanced control systems can help in transforming the present grid into one that functions more intelligently with better situational awareness, autonomous control for higher reliability, resiliency against failures, increase renewable energy penetration; active consumer participation, improved market efficiency, and higher quality of service [1.7]. The authors in [1.8] provide a comprehensive analysis for a case for microgrid citing the example of the CERTS microgrid. The need for reliable power which is supported using the example of the blackout in US in August 2003 which resulted in outages in large portions of North America and Canada with huge monetary loses. There are strict tolerances on power quality requirement (PQR) as specified by IEEE Standard 519-1992, subject to which the standard of acceptable power is decided based on most sensitive loads [1.9]. Since, a lot of loads may not need such a tight tolerance on power quality; it provides a case where such loads can be supplied with a lower quality power in case of emergencies and sustaining the outage. The EPS is a large interconnected system where generation sources are located far away from the loads and power is transmitted over long distances through transmission and distribution circuits. In this traditional power system it is not possible to selectively feed power to small number of loads without significant redesign to the existing infrastructure. If localized power generation exists, such a scenario is possible where small parts of loads or circuits can be isolated from the EPS and still be sustained through local power generation. The work in [1.8] also mentions economic benefits of the use of heterogeneous PQR by segregating loads into different categories and providing high PQR to sensitive loads. It also exploits the scenario of parts of load served based on the load type categorization – sensitive, adjustable, and shedable. This strategy is more prevalent in the military domain where loads to be shed are pre-determined load shedding scheme in different situations [1.11]. Importance of having localized generation and shedable loads is also brought out. On the other hand, [1.5] describes the emergence of sophisticated energy service requirements and intermittency due to integrated renewable energy sources; and hence the need for even higher PQR than in traditional power system. These distributed and renewable sources can serve purposes of local ancillary services such as VAR control in the local power system. Combined heat and power (CHP) is also an important source for making microgrids more economical given the fact that local waste heat is easier and economical to use for heating than the conversion from electricity or natural gas for some cases. The authors in [1.6] have also mentioned the evolution of the power system from small, regional, isolated systems to the present day interconnected power system which is more reliable than smaller systems. Such a high reliability has made a lot of other systems dependent on reliable power for optimal operation, thus a high degree of inter-reliance exists amongst power system and other critical infrastructure such as telecommunication. The other features mentioned in the CERTS microgrid is a single point of common coupling (PCC) which facilitates a single point of power exchange with the EPS and is also the point at which the microgrid can disconnect or island itself to be an isolated system. Such a feature also helps the microgrid to be viewed by the EPS as a single load, consuming power most of the time, in the long term operation. The two other features mentioned are the slow supervisory control for economic operation including scheduling and dispatch, and generator control by on-board power electronics. The former can be done through interface with energy management system (EMS) controlling load shedding assets for example, an EMS in a commercial building, while the latter can be done by extending the on-board capabilities of devices such as power flow controllers and differential current circuit breakers. Since, the inertia of the system changes in grid-connected and islanded mode, the control changes must be modified for different modes.

Traditional generation system has been successful due to economies of scale and the transmission system has maintained high reliability but has suffered from cascading failures. Due to high losses in stack and flue gas, the generation efficiency reaches a maximum of 35% [1.5]. With development of low cost technologies for integrating renewable and DER, economies of scale for conventional power system are being lost. Use of DER reduces the physical and electrical distance between power source and load. This enhances the voltage profile, reduces T&D losses, and helps in deferred investments in generation and transmission infrastructure [1.5]. Since, the size of the DER is much smaller compared to traditional generators; the number of such units required is higher. This not only brings up the issue of integration but also the control of these units. Controlling each unit individually is a difficult task; thus, these assets can be grouped together to form clusters and can be controlled through a central control system. Simple controls would prove more effective since complexity due to the large number of nodes to be controlled needs to be tackled. A single component failure in a complex system can bring down the whole system. The optimum placement of CHP and DER is mentioned in [1.6] for increased efficiency. The needs to serve higher PQR requirements due to newer, more sensitive loads can be met by controlling each cluster of assets and loads which can be treated as a single unit with known characteristics [1.6]. A centralized controller can be used for the coordinated operation of the microgrid and while the dynamic response can be provided by autonomous control system of the individual assets. This is important since due to the heterogeneity, assets have different response times and it becomes crucial for optimal control and stability during islanding. Different objectives can be achieved using DER in microgrids, namely high PQR with effective use of CHP, multi-MW microgrids, and high levels of solar photovoltaic microgrids. The concept of plug-and-play in peer-to-peer connection of microgrid assets can help meet the requirement of local loads without extensive re-engineering. Plug and play refers to interoperability through open standards and is defined in IEEE standard 1451.4-2004 [1.10]. This allows operation of products developed through different design standards and protocols to communicate with each other without any additional provision to establish communication. Storage is another important feature for microgrids. DC storage in form of batteries or supercapacitors can be used. This provides decoupling between source dynamics and microgrid thereby fast dynamic response. Using the above mentioned technologies, operational intelligence of distribution system can be enhanced. Such a distribution system can be used to achieve microgrid objectives of improved reliability, self-healing, simplified controls and increased generation efficiency through use of CHP [1.6], [1.8]. Integration of renewable energy introduces in a lot of intermittency in power system. Low capacity factors of sources, low correlation with load profile, high forecast errors for longer horizons, congestion at distribution level due to dispersed resources, and issues such as voltage regulation need to be mitigated using combination of other enabling technologies and control [1.8]. In addition to above, protective relaying, transformer configurations, harmonics, and location specific considerations would also play an important role. Since a major portion of the integration would be at the distribution level, studies to analyze distribution system to support such efforts are underway. The power industry has come a long way in terms of model and tool adoptions for analysis [1.12]. Many commercially available tools are being used to exploit the typical radial natures of medium and low voltage distribution and meshed network. Enhanced simulation capabilities have only accelerated the process of grid modernization. According to EPRI, the real time and planning analysis will merge in future. Detailed modeling, simulation and handling large volumes of advanced metering infrastructure (AMI) data are some of the prospective issues to be addressed [1.12].

Information technology (IT) infrastructure is an important enabler and support for better control in microgrids, especially for operating in parallel with EPS. Better telemetry, faster control devices, more robust controls, equipment level fault diagnostics, bad data identification, automatic equipment restoration, secure communication, and enhanced computing capabilities is possible with the effective use of IT [1.12]. Architectural hierarchy for various control systems can help provide more granularities at different levels. A multiple level agent based structure is proposed in [1.8], [1.13]. Various execution cycles can be designed for temporally coordinated functional tasks ranging from a few cycles to hours. Wide area monitoring system using phasor measurement units (PMUs) through North American Synchro Phasor Initiative (NASPI) involves gathering a lot of measurement data for better operation and diagnostics [1.14]. This clearly shows the current industry trend where the microgrids would be a crucial part of the grid modernization effort. RDSI projects are a big step in this regard and demonstrations have been done successfully in some locations and are underway in other locations. One of the nine RDSI projects was at Fort Collins, Colorado which has been successfully completed demonstration in 2011.The project aimed at feeder peak load reduction of 20-30% serving about 15MW of power to downtown Fort Collins and Colorado State University main campus. This demonstration has built and proved a strong case for a community scale microgrid and has brought out the practical issues faced when realizing such projects [1.15], **Error! Reference source not found.**.

1.4.2 Data reduction

This was the first step of data analysis from the dataset obtained from demonstration runs of FortZED RDSI spanning the period from June, 2011 to the beginning of September, 2011 [1.15], [1.16]. The data set had to be reduced to a form where more analysis and performance metric calculations can be done. These are explained in detail in Chapters 2 and 3 of the thesis. Major support in form of literature was obtained from MATLAB® documentation [1.17]. The tools and techniques to handle data, consistency checks and reduction were all done using MATLAB®. Some specific procedures of treating outliers, and pooling generation data for homogeneity were obtained using information in [1.18]. Since, the heterogeneity of assets in a microgrid is a differentiating factor, it becomes essential to treat each asset, generation and demand response differently when it comes to comparing their performance on a common scale. The report in [1.18] presents grouping and pooling of data from generating units based on certain characteristics as size, design for improved analysis. Sometimes the common attribute may come to ownership or a single control point and units are grouped together to estimate a system performance index even if units are otherwise not homogeneous. This method is employed during calculation of site performance metrics in form of weighted NERC metrics. The report also mentions using availability information over time to calculate metrics such as availability factor (AF). Treatment of outliers and excursions in large data sets had to be handled without sacrificing accuracy to extract maximum information from data because the sample size was small compared to usual data sets on which utilities make performance measure calculations. The run times may span months and even years while it was only approximately 50 hours for the FortZED RDSI demonstration. Outliers may give erroneous results, especially in a smaller data set when making calculations for individual asset [1.18], [1.19].

1.4.3 Performance metrics

Power system performance assessment is done using NERC metrics in North America. But, as microgrids find place in of modern power system, the importance of asset level reliability would increase for individual assets and groups of assets. Reference [1.4] gives the basic definitions and the mathematical formulas for the calculation of various performance assessment metrics. IEEE Standard 762-2006 states some more definitions and metrics used in reporting reliability, availability and productivity by electric utilities [1.20]. Since generation adequacy is the primary factors of power system performance, availability factor (AF) is an important metric. Reliability metric such as starting reliability (SR) is an appropriate measure to quantify performance for fast response in case of contingency. This holds even more importance in case of microgrids when it acts as a reserve and as an ancillary services provider when operating in parallel to the EPS. When operating in the islanded mode, the inertia of this system is lower than EPS so the SR of each asset can be crucial in dynamic stability of the power system. The next important performance measure is given by the net capacity factor (NCF) and the net output factor (NOF). Each of these quantifies the performance of an individual asset considering the actual output and capacity rating of the asset. Another metric, the service factor (SF) quantifies the percentage of time interval an asset has been in service when it was available. A higher value of each of these metrics: AF, SR, NCF, NOF, SF is better. Since, all these are expressed in percentages, lower and higher limits are 0 and 100% respectively. Average run time (ART) is a metric which gives average run hours per successful unit start, in hours. All these metrics are for individual assets and can be perceived slightly differently for microgrids than for the EPS.

Other metrics like weighted service factor (WSF) and weighted availability factor (WAF) are used for grouped assets. Since the EPS has most generators which fall largely in the same kind or type, for example nuclear, gas, coal, hydro, the necessity of selectively pooling assets is easier. For microgrids, the heterogeneity is vast, especially due to different types of sources and DR, which is an important feature to the microgrids. Weighted metrics can thus give a good perspective of group performance if pooled based on homogeneity. Choice of grouping can be based on various factors such as type of asset, location of asset, performance of asset, functional role of the asset in microgrid, i.e., whether it serves base load, peak load or some other ancillary service. Such a metric takes the individual asset rating into consideration, and does not average the result, thus a better judgment can be made using these performance metrics. Since peak load reduction was the main aim of this demonstration project, the calculations are made using traditional methods used by the DOE which uses the maximum peak loads from a load curve for a year [1.21].

Calculation of the metrics can provide information about performance of the microgrid. This information can be presented to the user in a form which is easier to understand. This is done using visualization which is reviewed in 1.4-d.

1.4.4 Visualization

Visualization in power system can be helpful in both the short and the long term planning and operation. Representation of information in a meaningful manner can help in enhanced situational awareness of the operator. Since, at times several variables have to be monitored manually, especially in the case of emergencies; decision making becomes easier if a visual tool is available for the operator to get a holistic perspective of the system. Troubleshooting becomes convenient with lot of information been presented in a simple format on an interactive platform. Such an arrangement can result in timely action and save major emergencies [1.22].

There has been a significant increase in transfer of large blocks of power from one region to another due to restructuring and deregulation of electricity market [1.23]. This has resulted in communication of data to entities far from their customers too. Congestion has resulted in rise of electricity price by a very large factor for a small duration, for example in June 1998, electricity prices in the mid-western US increased from US $ 25 to $ 7500 per MWh. The operator can make decisions to avoid such circumstances if timely information is available and increased situational awareness exists. To help this, visualization can be used which provides a clear picture of the status of large interconnected system and effects of power market on power system operation. Also, it is very difficult to comprehend the interaction of multiple variables in power system beyond a hundred or so entries [1.23]. Some other aspects discussed in [1.23] about visualization in electric grids are visualization of large volumes of data, use of contours for line parameter variations and trends, interactive visualization, three dimensional and perspective projection.

Large scale visualization projects are going on all around US, for example, NASPI is to visualize vast amount of data collected by PMU [1.14], [1.22]. This not only covers a large number of devices and measurements, but is also geographically vast. Various methods are being explored from contouring to pie charts for better visualization at required granularities [1.24]. Efforts are also underway towards determining, advancing and standardizing a visualization platform for the industry in seek of better interoperability and generalization in monitoring of power system [1.24]. A data driven approach is developed in [1.25] for powerful data manipulation algorithms for visualization based on empirically or mathematically derived data. The motivation is to shift the user into focus by presenting the relevant information and to reduce cognitive demands of the user. Visualization can help to uncover hidden patterns and trends in unknown data [1.26].

Since the data from FortZED RDSI runs was extensive due to large number of smaller capacity assets, the spread of data was the primary source of data presentation. Boxplots – notched and un-notched were plotted for each data set getting a fair idea about spread of data, outliers and quartile values [1.27], [1.28], [1.29]. MATLAB® documentation was used for developing GUI for data, metric display and visualization.

1.4.5 Software tools

MATLAB® was used for all the data analysis and the calculations. Visualization was done using the high level inbuilt functions and the GUI was also developed in MATLAB®. Simulink® was used for the process of sampling the unevenly time stamped data set to yield an evenly time stamped data set at a resolution of one second.

1.5 Organization of thesis

The thesis is organized in five chapters. Chapter 1 provides the introduction to the work done. Chapters 2 and 3 present the data processing, analysis and reliability metrics calculations. Algorithms and flowcharts are provided for clear representation wherever required. Chapter 4 deals with visualization of the information after the data analysis. The functionalities of the GUI for metrics and data visualization are explained in detail. Chapter 5 presents the results and future work in this area of research. Appendices-I and II contain data and MATLAB© program codes for analysis and visualization.

REFERENCES:

[1.1] DOE's smartgrid website, *'Recovery Act Smart Grid Programs – Overview of programs, studies and activities'* [Online], Available: http://www.smartgrid.gov/recovery_act/overview. Last Accessed: 9/24/2012.

[1.2] DOE media release, '*DOE Selects Projects for up to $50 Million of Federal Funding to Modernize the Nation's Electricity Grid*', [Online], Available: http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/4.21.08_Renewable_Distributed_Systems_Awards.pdf. Last Accessed: 9/24/2012.

[1.3] *IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems*, IEEE Std 1547.4-2011, pp. 1 –54, 2011.

[1.4] NERC Generating Unit Statistical Brochure, October 2008 [Online], Available: http://www.nerc.com/page.php?cid=4%7C43%7C47. Accessed 8/14/2012.

[1.5] Lasseter, R.H. "Smart Distribution: Coupled Microgrids." *Proceedings of the IEEE vol.* 99, no. 6 (June 2011): 1074 –1082.

[1.6] C. Marnay and G. Venkataramanan, "Microgrids in the evolving electricity generation and delivery infrastructure," in *IEEE Power Engineering Society General Meeting, 2006*, 2006, p. 5 pp.

[1.7] K. Moslehi and R. Kumar, "Smart Grid - a reliability perspective," in *Innovative Smart Grid Technologies (ISGT), 2010*, 2010, pp. 1 –8.

[1.8] C. Marnay, O.C. Bailey, 'The CERTS Microgrid and the Future of the Macrogrid', [Online], Available: http://certs.lbl.gov/pdf/55281.pdf. Last Accessed: 9/30/2012.

[1.9] *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*, IEEE Std 519-1992, p. 0_1, 1993.

[1.10] *IEEE Standard for a Smart Transducer Interface for Sensors and Actuators - Mixed-Mode Communication Protocols and Transducer Electronic Data Sheet (TEDS) Formats*, IEEE Std 1451.4-2004, pp. 0_1 –430, 2004.

[1.11] Z. Ding, S. K. Srivastava, D. A. Cartes, and S. Suryanarayanan, "Dynamic Simulation Based Analysis of a New Load Shedding Scheme for a Notional Destroyer Class Shipboard Power System," in *IEEE Electric Ship Technologies Symposium, 2007. ESTS '07*, 2007, pp. 95 –102.

[1.12] R. C. Dugan, R. F. Arritt, T. E. McDermott, S. M. Brahma, and K. Schneider, "Distribution System Analysis to support the Smart Grid," in *Power and Energy Society General Meeting, 2010 IEEE*, 2010, pp. 1 –8.

[1.13] S. Suryanarayanan, J. Mitra, and S. Biswas, "A conceptual framework of a hierarchically networked agent-based microgrid architecture," in *Transmission and Distribution Conference and Exposition, 2010 IEEE PES*, 2010, pp. 1 –5.

[1.14] NAPSI website, [Online], Available: https://www.naspi.org/ Last accessed 10/8/12

[1.15] D. Zimmerle, 'A Community Scale Microgrid Demonstration: FortZED/RDSI', *IEEE PES GM 2012*, July, 2012.

[1.16] M. Panwar , G.P. Duggan, R.T. Griffin, S. Suryanarayanan, D. Zimmerle, M. Pool, S. Brunner, "Dispatch in microgrids: Lessons from the Fort Collins Renewable and Distributed Systems Integration demonstration project", *The Electricity Journal* (Article in Press), [Online], Available, http://dx.doi.org/10.1016/j.tej.2012.09.011

[1.17] MATLAB Documentation, [Online], Available: http://www.mathworks.com/help/matlab/index.html

[1.18] Final Report of the Task Force on Generation Unit Data Pooling: '*Pooling generating unit data for improved estimates of performance indices*', May1995, [Online], Available: http://www.ece.tamu.edu/People/bios/singh/reports/gudp1.pdf

[1.19] Montgomery, D. C., Runger, G. C. (1999). *Applied statistics and probability for engineers.* 2nd ed. New York: J. Wiley

[1.20] "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems," *IEEE Std 519-1992*, p. 0_1, 1993.

[1.21] M. Smith, Presentation - 'Overview of the U.S. Department of Energy's Research & Development Activities on Microgrid Technologies' , *2009 San Diego Symposium on Microgrids* [Online], Available: http://der.lbl.gov/sites/der.lbl.gov/files/smith.pdf

[1.22] J.H. Obradovich, Alison Silverstein, 'North American Synchrophasor Initiative (NASPI) Phasor Tools Visualization Workshop- Final Report', February 28, 2012, [Online], Available: https://www.naspi.org/ pp. 3-4.

[1.23] Visualizing the Electric Grid - Article, Thomas J. Overbye, James D. Weber, February 2001,[Online], Available: http://spectrum.ieee.org/energy/the-smarter-grid/visualizing-the-electric-grid/0

[1.24] T. J. Overbye and J. D. Weber, "New methods for the visualization of electric power system information," in *IEEE Symposium on Information Visualization, 2000. InfoVis 2000*, 2000, pp. 131 –16c.

[1.25] Y. ZiJian, S. Peng, L. XiaoMei, and Z. Wei, "Design and implementation of visualization platform in power system," in *2011 International Conference on Advanced Power System Automation and Protection (APAP)*, 2011, vol. 2, pp. 853 –856.

[1.26] J. Zhu, E. Zhuang, C. Ivanov, and Z. Yao, “A Data-Driven Approach to Interactive Visualization of Power Systems,” *IEEE Transactions on Power Systems*, vol. 26, no. 4, pp. 2539 –2546, Nov. 2011.

[1.27] M. Frigge, D.C. Hoaglin and B. Iglewicz, “Some Implementations of the Boxplot”, *The American Statistician,* Vol. 43, No. 1 (Feb., 1989), pp. 50-54, [Online], Available: http://www.jstor.org/stable/2685173

[1.28] R.McGill, J.W. Tukey and W.A. Larsen, ”Variations of Box Plots”, *The American Statistician,* Vol. 32, No. 1 (Feb., 1978) (pp. 12-16),[Online], Available: http://www.jstor.org/stable/info/2683468

[1.29] Y. Benjamini, “Opening the Box of a Boxplot”, *The American Statistician,* Vol. 42, No. 4 (Nov., 1988) (pp. 257-262),[Online], Available: http://www.jstor.org/stable/info/2685133

Chapter 2

Data processing, handling and reduction

This chapter presents an overview of FortZED RDSI demonstration project and provides a discussion of data reduction for convenient follow up to the process of data analysis.

2.1 FortZED RDSI microgrid demonstration project

The following two sections define the FortZED Renewable and Distributed System Integration or FortZED RDSI project in detail and features of dispatch and control methodologies followed during test demonstrations.

2.1.1 About the project

The FortZED Renewable and Distributed System Integration (RDSI) project is a US Department of Energy (DOE) program, started in 2009, with the objective of encouraging the use of distributed resources to reduce peak load demand by 20-30 percent of total feeder load [2.1]. The prime contractor for the Fort Collins RDSI project was the City of Fort Collins Utilities. Project funding consisted of \$6.3 million from the DOE, and nearly \$5.1 million in state and local investments. The purpose of this RDSI project was to develop and demonstrate a system of distributed generation (DG) resources that can operate in a coordinated manner to reduce the peak load on two distribution feeders by at least 20% which was much above the DOE aim of 15% of total feeder load on a distribution feeder or substation. Another goal of the FortZED RDSI project was to provide a strong start to a longer-term goal for the city of Fort Collins: developing a zero energy district – the “Fort Collins Zero Energy District” or FortZED –

encompassing portions of the downtown area and the Colorado State University campus, as shown in Figure 2.1.

FortZED represents approximately 10-15% of the Fort Collins Utilities (FCU) distribution system. The vision is to extend FortZED to a larger, 45-50 MW implementation in the near future. While the main focus of the RDSI project was on reducing the peak feeder load, research and development was also performed on a number of new technologies like waste heat recovery system, vehicle to grid (V2G) and photovoltaic simulator in conjunction with the microgrid demonstration. The primary objective of RDSI is to encourage coordinated participation of integrated renewable and distributed energy resources in peak load reduction. The general philosophy of peak load reduction is given in Figure 2.2 wherein the intended peak load is decreased during the period when a control signal, identified as *RDSI*, is engaged.

The project was performed in three phases, each with duration of one year. The site upgrades and new asset installations were completed in first two years and the configured system was demonstrated in a series of test runs between June 2011 and early September 2011. Since the first two test periods helped in establishing the system for the best performance, the third test run period was chosen for analysis to obtain concrete results about performance of the microgrid demonstration. Here the data processing and handling is presented for the full demonstration period but data reduction and analysis is done only for the third test period spanning August 15, 2011 to September 1, 2011.

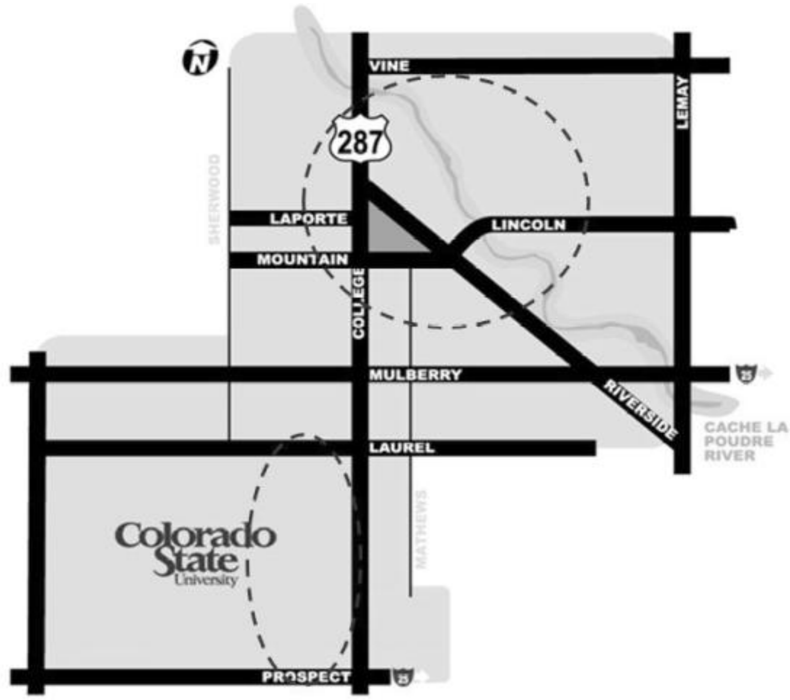


Figure 2.1 FortZED district (shaded grey) and the area covered by the feeders under the RDSI study [2.1]

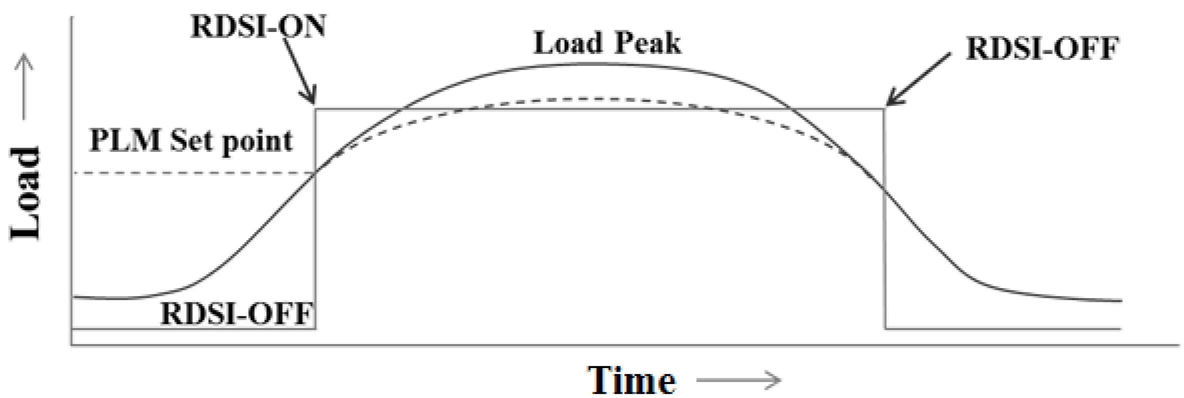


Figure 2.2 Illustrative diagram of peak load Reduction in RDSI [2.1]

There was no test run on September 2, 2011 because the load on feeder was lower than the set-point and hence FortZED RDSI system was not engaged. So, henceforth in this work the third demonstration period is referred to as period spanning August 15 to September 1, 2011.

Entities which participated in RDSI were classified into different types based on their functional role in the project. Colorado State University (CSU), City of Fort Collins (CFC), Larimer County, New Belgium Brewing Company (NBB) and the Engines and Energy Conversion Lab (EECL) – an off-campus laboratory of CSU – were the identified site partners that had deployable load shedding and generation assets. The total capacity was approximately 5 MW, as shown in Table 2.1. The capacity during demonstration runs was lower than original due to unavailability of assets. The technological features of the assets included application of advanced mixed-fuel technology, advanced generator controls, low-cost grid parallel switchgear, a micro-wind turbine, solar photovoltaic panels, solar thermal systems, solar electric systems, LED and CFL lights, fuel cells, hybrid engines, and plug-in hybrid electric vehicles (PHEV). Spirae Inc. [2.2], Brendle Group [2.3], Woodward Inc. [2.4], Advanced Energy [2.5], Eaton [2.5], and VanDyne Inc. [2.7] were the identified technical partners that provided the technical upgrade, retrofit and logistics support for various sites and assets. US DOE provided a grant for the project with matching funding provided by the Woodward Foundation, Fort Collins Downtown Development Authority, Bohemian Foundation, and the Community Foundation of Northern Colorado. The site partners also contributed various levels of matching funds. The site partners housed the assets for load dispatch and were categorized as demonstration and R&D sites [2.1].

Conventional sources of generation and load shedding assets formed the largest portion of RDSI capacity during the demonstration. Demand side management (DSM) was performed through other sites such as City of Fort Collins, Colorado State University, Larimer County courthouse, and New Belgium Breweries which had combinations of load shedding assets including HVAC, water fountains, and cooling systems which were dispatched to reduce power consumption. All the systems were integrated through communication links working over the Distributed Generation Network Operating System (DERNOS), which is a proprietary interface connected to the main control center at one of the sites for the RDSI project demonstration. The control center was located at the facilities of one of the partner institutions. All the control commands were issued through this control center using the peak load management (PLM) program that dispatched assets for load shedding or generation depending upon the incident peak load. The algorithm specifically took into consideration the asset types, cost of operation, efficiency and emissions before issuing a command to any asset. Tables 2.1 and 2.2 list the site and asset identifiers.

Table 2.1 RDSI capacity summary

Location	**Site identifier**	**Original (kW)**	**Demonstration period 3 (kW)**
City of Fort Collins Operation Services	*cfc*	849	785
CSU Department of Facilities Management	*csu*	1201	746
CSU EECL	*eecl*	1335	325
InteGrid Laboratory	*int*	320	220
Larimer County Facilities Department	*lar*	29	34
New Belgium Brewing Company	*nbb*	1279	1279
Grand Total	***rdsi***	**4958**	**3389**

The original power ratings and the availability during the third period of demonstrations is also shown. The third phase spanned from August 15, 2011 to September 1, 2011 and the FortZED RDSI asset capacity during third phase and originally planned is shown in Table 2.1.

2.1.2 Scheduling, dispatch, and control methodologies

The time period for which test runs could be conducted was a constraint for asset scheduling and load dispatch. Therefore, asset scheduling was done on a round-robin basis to maximize asset participation. The target load set point for the control software was entered manually into the SCADA system. PLM set the site priorities for a particular test day and set asset dispatch priority for every asset at each site before the start for the test run. The site priorities rotated in the order from '0' (highest) to '6' (lowest) to allow each site to have the highest priority once in every rotation. The PLM algorithm assigned asset index ranging from '0' (highest) to '29' (lowest) for any given site depending on nature of asset, i.e., uncontrollable asset (index: 0-9); load shedding (index:10-19); and, generation (index: 20-29). Each site also had the option to set asset priority if needed. Load shed (index: 0-209) and generation priority index (index 210-419) for any given day was calculated based on (2.1) and (2.2), respectively.

Table 2.2 Ratings of FortZED RDSI assets listed with sites and identifiers

Asset name (identifier)	Rating (kW)	Description / type of asset
cfc Gen01	291.00	City Hall Gen-set (Conventional Gen)
cfc Ldf01	29.00	City Hall HVAC (Demand Response)

Asset name (identifier)	Rating (kW)	Description / type of asset
cfc Ldf02	67.00	215 N. Mason HVAC (Demand Response)
cfc Ldf03	11.00	117 N. Mason HVAC (Demand Response)
cfc Ldf04	52.00	NSAC HVAC (Demand Response)
cfc Ldf05	16.00	Ops. Svcs. HVAC (Demand Response)
cfc Ldf06	46.00	281 N. College HVAC (Demand Response)
cfc Ldf07	20.00	Streets HVAC (Demand Response)
cfc Pv01	5.00	215 N. Mason PV (Solar Photovoltaic)
cfc Pv02	51.00	NASC PV (Solar Photovoltaic)
csu Gen01	24.00	NESB (Conventional Gen)
csu Gen02	114.00	GreenHouse (Conventional Gen)
csu Gen04	700.00	Steam Plant CHP (Combined heat & power)
csu Ldf01	191.00	Fans Group 1 (Demand Response)
csu Ldf02	83.00	Fans Group 2 (Demand Response)
csu Ldf03	22.00	Fountain Control (Demand Response)

Asset name (identifier)	Rating (kW)	Description / type of asset
csu Pv03	17.00	Behavioral Sciences PV (Solar Photovoltaic)
eecl Gen01	228.00	Caterpillar genset (Conventional Gen)
eecl Gen02	260.00	Cummins genset (Conventional Gen)
eecl Gen03	10.00	Fuel Cell (R&D)
eecl Gen04	20.00	Waste Heat Unit (Generation – R&D)
eecl Gen05	350.00	VanDyne Genset #1 (Conventional Gen-R&D)
eecl Gen06	140.00	VanDyne Genset #2 (Conventional Gen-R&D)
int Gen02	59.00	Onan Genset #1 (Conventional Gen)
int Gen03	59.00	Onan Genset #2 (Conventional Gen)
int Gen04	100.00	Wind Simulator (R&D)
lar Ldf01	1.50	Fountain Control (Demand Response)
lar Pv01	26.82	PhotoVoltaics@Admin (Solar Photovoltaic)
nbb Gen01	522.00	500kW genset -New Guascor Unit (Conventional Gen)
nbb Gen02	292.00	292 kW genset -Gauscorp (Conventional Gen)

Asset name (identifier)	Rating (kW)	Description / type of asset
nbb Ldf01	85.00	load Shedding #1 (Demand Response)
nbb Ldf02	52.00	Load Shedding #2 (Demand Response)
nbb Ldf03	150.00	Thermal Storage (Demand Response)
nbb Pv01	200.00	Photovoltaics- PV Array (Solar Photovoltaic)

The formulas (2.1) - (2.3) indicate that load-shedding assets had higher priority than generation assets, as it was an economically better decision to first curtail consumption before engaging additional generation. The control then tracked the combined load on two feeders. When the load exceeded the set point, available capacity for each asset was summed in order of priority until the projected load matched the set point value. The selected units were then dispatched in order of asset dispatch priority scheduled by the PLM. To allow sufficient time for units to respond, the PLM was delayed for further correction by 3 minutes from the point in time when control command was issued. The response monitoring time was 3 minutes for assets below 250kW rating before adjusting any dispatch instructions. An addition delay of 3 minutes was introduced if any of the dispatched assets had a capacity rating above 250 kW. This allowed larger assets sufficient time to ramp and stabilize. No more than 500 kW of net load from FortZED RDSI system was dispatched by PLM at any one time to maintain stability and avoid sudden feeder fluctuations. Once the PLM set point was reached, the feeder load was monitored and control signals for output corrections were given every 15 seconds. This was done through spinning reserve assets located at the EECL. The spinning reserve contribution was linearly distributed among the running reserve assets as per the respective rated capacity. This reserve set point is defined in (2.3) below. Formulas for priority selection in the PLM algorithm for RDSI demonstration are also provided.

Load shed priority = (Site index)*30 + (Asset index) (2.1)

Generation priority = 210 + (Site index)*30 + (Asset index) (2.2)

Reserve set point = (Asset rating * Adjustment required) / (Total spinning reserve) (2.3)

This adjustment from spinning reserves was limited to a maximum of 50 kW on each update cycle to avoid an oscillatory effect on the system due to spinning reserve assets. When the net feeder load reduced below the set point, assets were switched off in reverse order of asset dispatch priority. During this time a lower level dead band was employed to avoid sudden and early release of an asset due to feeder load fluctuations. The run time for each asset was constrained between a minimum and maximum value, typically 30 minutes and 4 hours respectively. Once an asset was called and released, it was not called again within that test day.

Rule of load shed and generation priority based on (2.1) – (2.3) can be considered as a rule of thumb. Load scheduling and dispatch was controlled as per an algorithm from one of the participating entities. Each period of test runs which was around 12 days with restrictions on the allowable runtime for diesel generators. As per EPA norms and CDPHE these are restricted to about 4 hours per day. Thus, the total run time was approximately 48 hours per test phase and during this limited period of demonstration, maximum asset participation was chosen as a criterion for schedule and dispatch methodology.

For peak shaving, the assets to be dispatched were decided using a method that made utilization and participation of a maximum number of assets. This was based on the nature of the asset being a DR type or a generator. An alternate method could be on basis of random selection of assets and schedule it as per the type of asset and dispatch as per the given set point.

So, the process of asset dispatch in a microgrid can be divided into following successive decision steps:

1. Selection of feeder load set point at which dispatch starts

2. Selection of assets (site-wise or random or as per performance metrics like starting reliability, service factor or some other asset level NERC metric)

3. Selection of scheduling order (queuing in some selected order of priority- either random or as per performance metrics like starting reliability, service factor or some other asset level NERC metric)

Emergency first up action, including planning of spinning reserves and rescheduling the resource capacity can be done if available capacity is less than required dispatch capacity as per current feeder load. This justifies a case for identifying and designing microgrids with capacity to suffice peak shaving as well as provide appropriate amount of spinning reserves ensuring that the microgrid is not over designed to avoid stranding of assets. This method was preferred over some of the existing methods of dispatch that aim at cost reduction or risk limitation. All of these methods require a substantial amount of information about the operational performance of the assets. As the test run periods were short, this historical information could not be used for scheduling and dispatch.

There were several operational constraints during the test runs that limited dispatch options for FortZED RDSI. The most important of these were air emission restrictions. As indicated above, sites were scheduled on a round-robin basis. This allowed all sites to participate equitably, and also minimized the difference in unit run times between similar units at different sites. However, run time for the backup generators was restricted to a certain number of hours per year to satisfy emission standards. Since most sites with backup generation needed to reserve some run time for emergency conditions, emissions restrictions further constrained the dispatch of generators.

In other cases, such as generators located at a research laboratory like the EECL, emissions standards were less of an issue, enabling greater participation of generation assets at these sites. Usually, emergency power generators with ratings less than 1840 hp and running less than 100 hours annually, rating less than 737 hp and running less than 250 hours annually, or rating less than 260 hp are exempt from Air Pollution Emission Notice (APEN) as required by (CDPHE). Permission to run for 800 hours per year was obtained from CDPHE for the backup generators at CSU (two generators of 134 hp & 257 hp) and EECL (one generator of 735 hp). This included routine as well as test runs. Since the generators were used for peak load management during test runs, a provision for a grouped permit was obtained to ensure that their APEN exemption was not lost. A maximum runtime of 800 hours per year amounts to approximately 66 hours per month for each asset, assuming equal usage of the asset throughout the year. Thus, for a 15 day test schedule, runtime was restricted to about 4 hours per day.

It is important to note that certain generation units at the academic and research facilities like CSU and EECL, and specifically biogas and natural gas units at NBB were permitted to run longer than 4 hours per day under different rules that supported substantially longer annual run times, due to the low emissions from these units. The heterogeneous mix of assets resulted in a reduced CO_2 emission footprint. Average Net CO_2 emission factor comparison for different asset types is shown in Figure 2.3 where emissions reductions are indicated as negative and emissions increases are shown as positive. Amended APEN approvals were obtained for generation assets at other sites since getting a newer APEN was more difficult than a modifying an existing one. Finally, since load-shedding assets had preference over generation assets, dispatch of DR assets was tested more frequently and more extensively than generation assets. The combination of real-world restrictions on unit operation limited the experimental variation in dispatch operation during the test runs, and therefore limited, to some extent, the insights that could be gained. However, these restrictions represent a real-world scenario, which will be encountered in any practical microgrid with a diverse asset base.

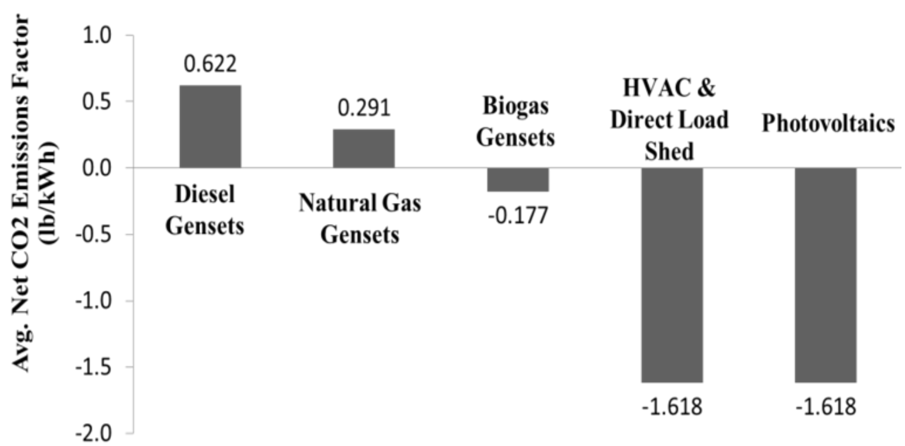


Figure 2.3 Average net carbon dioxide emissions per unit electricity generated or saved through different kinds of generation and load shedding assets [2.1]

2.2 RDSI demonstration data

The test runs for RDSI demonstration were performed in three phases during the months of June, July, and, August in 2011. The first two test periods had several assets which either failed to operate over long periods or were removed from tests due to economic reasons. Thus, these initial test runs helped in finalizing the group of assets which participated in the final demonstration period spanning August 15, 2011 to September 02, 2011. Each test period was in the range of 10 to 15 days, at approximately 4 to 5 hours per day covering the peak load periods. There were 40 assets that participated in the first and second phase and 35 assets that participated in the third phase of test runs. The total planned asset capacity was approximately 5 MW but only 3 MW was available during the final phase of the demonstration. Since, there were a large number of assets operating for about 40 to 50 hours per test period, a large amount of test data was generated during the demonstration. MATLAB® was used for the analysis and data reduction presented here.

2.3 Nature of test data

The RDSI test run data was obtained from a traditional SCADA system used in operation and control in electric power industry [2.8]. Electric power output (in kW) and commands initiated by control system for asset dispatch were stored in separate text files (CSV format). The command set nomenclature for generation and demand response type assets is shown in Tables 2.3 and 2.4 respectively.

Table 2.3 Control system nomenclature for generation type assets

Command nomenclature	Operation
0	OFF
8704	OFF
8708	BASE LOAD
8710	MAXIMUM LOAD

Table 2.4 Control system nomenclature for demand response type assets

Command nomenclature	Operation
0	NORMAL
2	NORMAL
66	SHED LOAD

The data files from SCADA system were arranged separately as command and power output files. Tables 2.5 and 2.6 show portions of command and power file respectively. This is for a generation asset at NBB. The first column in Table 2.5 contains the name of the asset in SCADA files; second and third columns contain the time stamps and command values respectively.

Table 2.5 Command file for generator at NBB

SCADA file asset name	Time stamp	Command
Sites.NBB.Gen02.GEN.CCWc	8/23/2011 12:56:11PM	8,704.00
Sites.NBB.Gen02.GEN.CCWc	8/23/2011 12:59:26PM	8,704.00
Sites.NBB.Gen02.GEN.CCWc	8/23/2011 12:59:29PM	8,704.00
Sites.NBB.Gen02.GEN.CCWc	8/23/2011 12:59:59PM	8,704.00
Sites.NBB.Gen02.GEN.CCWc	8/23/2011 1:00:02PM	8,704.00
Sites.NBB.Gen02.GEN.CCWc	8/23/2011 1:07:44PM	8,710.00

The first column in Table 2.6 contains the name of the asset in SCADA files, second and third columns contain the time stamps and power output values in kilowatt respectively.

Table 2.6 Command file for generator at NBB

SCADA file asset name	Time stamp	Power output (kW)
Sites.NBB.Gen02.PMR.P__m	8/23/2011 12:31:50PM	0
Sites.NBB.Gen02.PMR.P__m	8/23/2011 12:31:53PM	0
Sites.NBB.Gen02.PMR.P__m	8/23/2011 12:58:08PM	65,535.00
Sites.NBB.Gen02.PMR.P__m	8/23/2011 12:58:11PM	0
Sites.NBB.Gen02.PMR.P__m	8/23/2011 1:00:02PM	0
Sites.NBB.Gen02.PMR.P__m	8/23/2011 1:00:05PM	0
Sites.NBB.Gen02.PMR.P__m	8/23/2011 1:07:53PM	65,534.00
Sites.NBB.Gen02.PMR.P__m	8/23/2011 1:10:56PM	65,533.00
Sites.NBB.Gen02.PMR.P__m	8/23/2011 1:11:02PM	65,529.00
Sites.NBB.Gen02.PMR.P__m	8/23/2011 1:11:08PM	65,528.00
Sites.NBB.Gen02.PMR.P__m	8/23/2011 1:11:44PM	65,529.00
Sites.NBB.Gen02.PMR.P__m	8/23/2011 1:11:59PM	65,535.00
Sites.NBB.Gen02.PMR.P__m	8/23/2011 1:12:02PM	5
Sites.NBB.Gen02.PMR.P__m	8/23/2011 1:12:08PM	15
Sites.NBB.Gen02.PMR.P__m	8/23/2011 1:12:11PM	23
Sites.NBB.Gen02.PMR.P__m	8/23/2011 1:12:17PM	35
Sites.NBB.Gen02.PMR.P__m	8/23/2011 1:12:20PM	49
Sites.NBB.Gen02.PMR.P__m	8/23/2011 1:12:23PM	65

Major challenges in data reduction were:

1. Unevenly time stamped data
2. Repetitive time stamps in original data files
3. Non-alignment of command and power values in time for an asset
4. Power value excursions.

Power and command data was stored in two separate files for each site. Each file contained data corresponding to all the assets in time. The data points were time stamped to a resolution of one second. Since dead band capture is employed for data acquisition for efficient data storage, the data was unevenly time-stamped. This data, as present in the native form, could not be used for a comprehensive analysis in time domain.

Figure 2.4 shows plots of time stamps for one of the assets. It can be easily observed that the slope is not constant and time values do not vary evenly at consecutive time samples. This is true for both command and power output data sets. The number of samples for command and power value time stamp also differs considerably for the same asset.

Table 2.7 shows the percentage of repetitive time stamps for each asset. These occur in the original data files and can be attributed to erroneous data capture or storage. Only unique time stamps are retained for further data processing. As seen in the Figure 2.4, the time stamp values of the asset do not match for the command and power output of an asset.

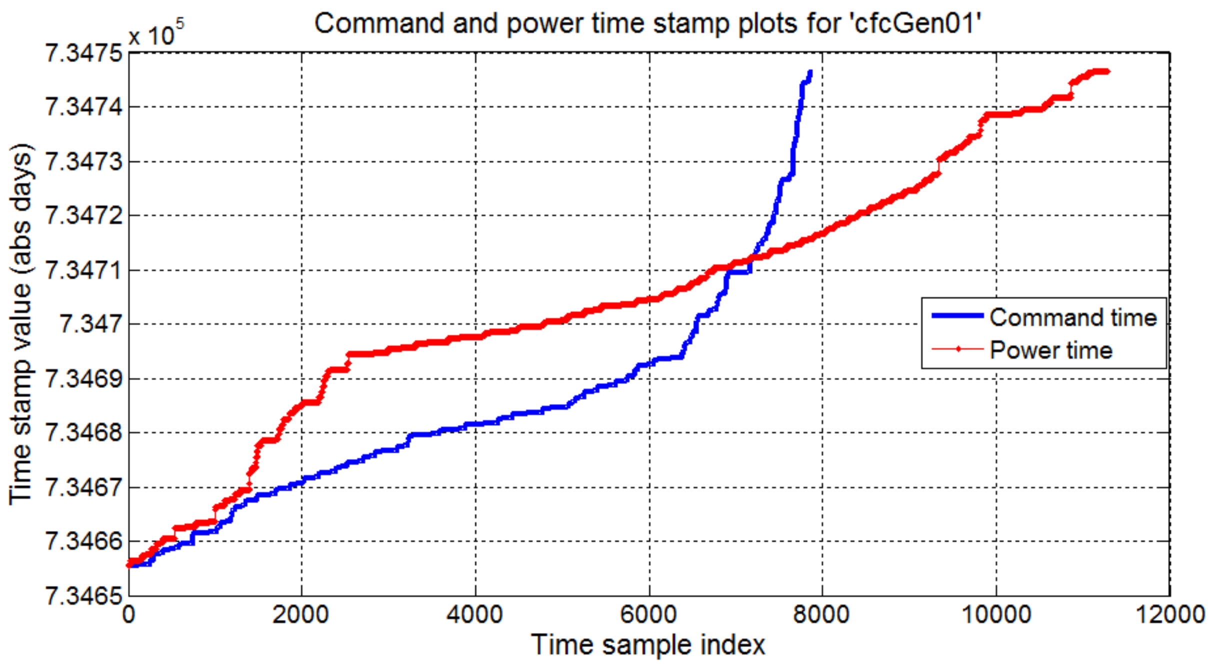


Figure 2.4 Command and power time stamps comparison for 'cfcGen01'

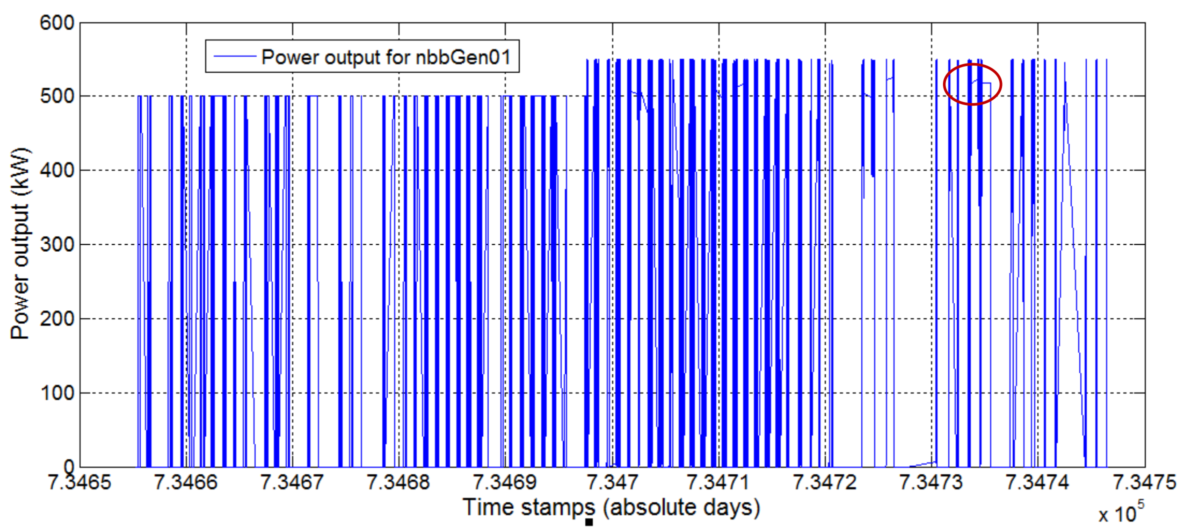


Figure 2.5 Example of power values plotted against time stamps for Gen01 at NBB. The portion of the plot encircled in red is shown in Figure 2.6

Thus, this non-alignment would not allow satisfactory data analysis in time. For example, if the total output of group of assets in a system is to be calculated, it cannot be done until all data samples are aligned in time. Only then, summing up of outputs is possible.

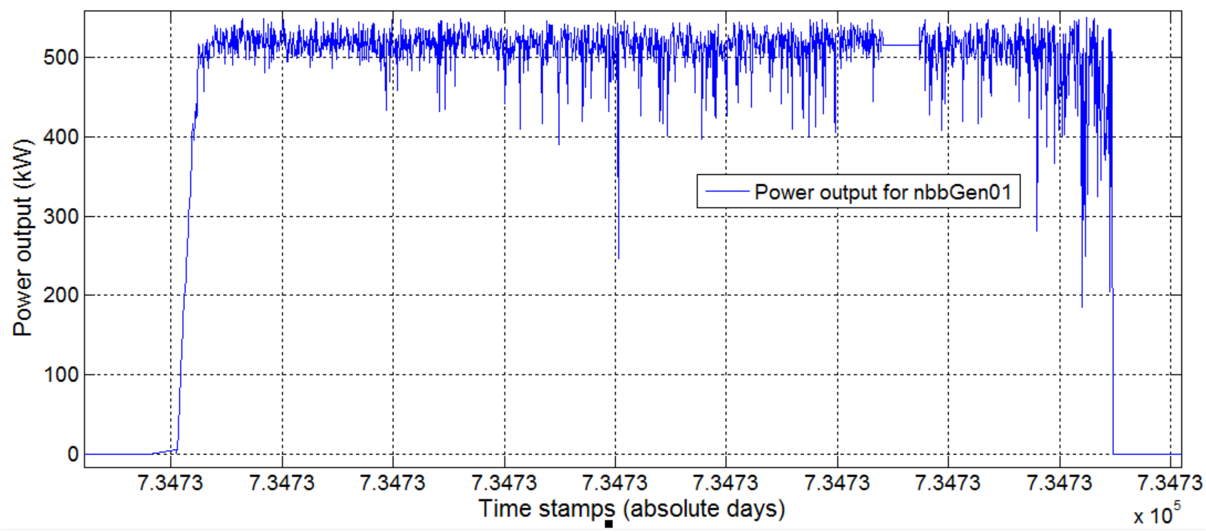


Figure 2.6 Example of power values plotted against time stamps for *nbbGen01*

Figures 2.5 and 2.6 show the power data plotted against the respective time vector. The asset named *nbbGen01* is rated at 522 kW (refer Table 2.2) while a few data points lie above the rating.

The high value excursions, if any, are removed and can be attributed to data acquisition or storage in SCADA system. These excursions have to be treated selectively based on the type of asset before any analysis for meaningful results can be done. The methods employed to treat this data are described in data processing section of this chapter.

Table 2.7 Power and command time vector repetitions in CSV files for each asset

Asset name (identifier)	Command time stamps vector			Power time stamps vector		
	Total vector length	Repetitive time stamps		Total vector length	Repetitive time stamps	
		Vector length	As % of total set		Vector length	As % of total set
cfc Gen01	7870	6	*0.08*	11308	7	*0.06*
cfc Ldf01	16956	6	*0.04*	15278	6	*0.04*
cfc Ldf02	22593	8	*0.04*	8933	17	*0.19*
cfc Ldf03	22592	7	*0.03*	11104	21	*0.19*
cfc Ldf04	22594	8	*0.04*	17425	30	*0.17*
cfc Ldf05	22592	8	*0.04*	28567	39	*0.14*
cfc Ldf06	22591	8	*0.04*	57756	65	*0.11*
cfc Ldf07	22591	7	*0.03*	23124	9	*0.04*
cfc Pv01	7693	5	*0.06*	24540	26	*0.11*
cfc Pv02	1992	3	*0.15*	9793	18	*0.18*
csu Gen01	5357	3	*0.06*	25435	1	*0.00*
csu Gen02	5351	3	*0.06*	12568	2	*0.02*
csu Gen04	5262	3	*0.06*	440266	62	*0.01*
csu Ldf01	10302	4	*0.04*	444287	122	*0.03*
csu Ldf02	10250	3	*0.03*	8141	3	*0.04*
csu Ldf03	10282	4	*0.04*	7095	3	*0.04*

Asset name (identifier)	Command time stamps vector			Power time stamps vector		
	Total vector length	Repetitive time stamps		Total vector length	Repetitive time stamps	
		Vector length	As % of total set		Vector length	As % of total set
csu Pv03	5264	1	*0.02*	96524	64646	*66.97*
eecl Gen01	10332	3	*0.03*	63235	1	*0.00*
eecl Gen02	10239	0	*0.00*	6686	0	*0.00*
eecl Gen03	10232	0	*0.00*	17299	0	*0.00*
eecl Gen04	10227	0	*0.00*	5679	0	*0.00*
eecl Gen05	9588	0	*0.00*	9593	1	*0.01*
eecl Gen06	10219	0	*0.00*	5080	1	*0.02*
int Gen02	2716	1777	*65.43*	29364	1702	*5.80*
int Gen03	2692	1758	*65.30*	30225	1705	*5.64*
int Gen04	2722	1845	*67.78*	5413	1868	*34.51*
lar Ldf01	8356	5	*0.06*	2421	7	*0.29*
lar Pv01	1977	4	*0.20*	23016	37	*0.16*
nbb Gen01	12581	5	*0.04*	133105	21	*0.02*
nbb Gen02	12571	5	*0.04*	71030	11	*0.02*
nbb Ldf01	17327	3	*0.02*	11217	3	*0.03*
nbb Ldf02	17293	3	*0.02*	14101	4	*0.03*
nbb Ldf03	17329	1	*0.01*	18088	5	*0.03*
nbb Pv01	12475	4	*0.03*	31305	1	*0.00*

2.4 Data processing

The reason for sampling data was to have information of each asset output at every time sample. This would make the data consistent in time for any further analysis. Some performance metrics require the system response to be quantified as a function of control system commands. Thus, both power and command values were sampled in time. Since the resolution of the command and power value data in CSV files was one second, data for all the assets was also sampled at resolution of one second.

The first challenge was to process the data to obtain a command and power output time series for every asset. Sampling and holding the data to the previous value till a new data point occurs in the compressed data sequence helped overcome the above challenge. The data was then analyzed as per definitions of the required input factors to the metric calculations and the performance metrics calculated for every asset and site as per NERC criterion [2.9]. The test run data when obtained at a resolution of one second required careful handling and verification at each step of data set manipulation. The format of time stamps stored in CSV files had to be changed manually to read the files as CSV format. To avoid this manual intervention, the data had to be read in as *string* on a field wise basis. This took about 18 minutes to read all the data files in MATLAB (version7.11.0 R2010b) running on Windows® 7 platform computer. Since, this was a one-time operation and static data analysis; the data from the files were read in the MATLAB™ workspace and stored as data structures with multiple levels of sub-structures consisting of power, command, and time data. Any dynamic or real time data analysis operation would require data to be stored in a format convenient for real time or near real time processing.

The original time stamped data had to be interpolated at a uniform time interval and resolution of one second. The software used for data reduction did not have an in-built function with this characteristic. Procedural programming using recursive function loops for large data set was not a primary choice due to slow speed of such operation. Thus, a Simulink® model was used to replicate the characteristic of a zero-order hold system. The interpolated data obtained was cross-checked with the original data to avoid any data loss or errors. The data set obtained contained evenly time stamped data with a resolution of one second. The command values for generation and DR assets were also converted to smaller integer values which were used as unique identifiers in command data set. The *modulus after division* operator was used to obtain new values for command data set. For 0, 8704, 8708, 8710, 2, and 66, the new commands reduce to 0, 4, 8, 10, 2, and 6 respectively. Table 2.9 shows the transformed command data set. This reduction was done to obtain a better visual appreciation while plotting power output and command values in time to observe asset response and for further analysis.

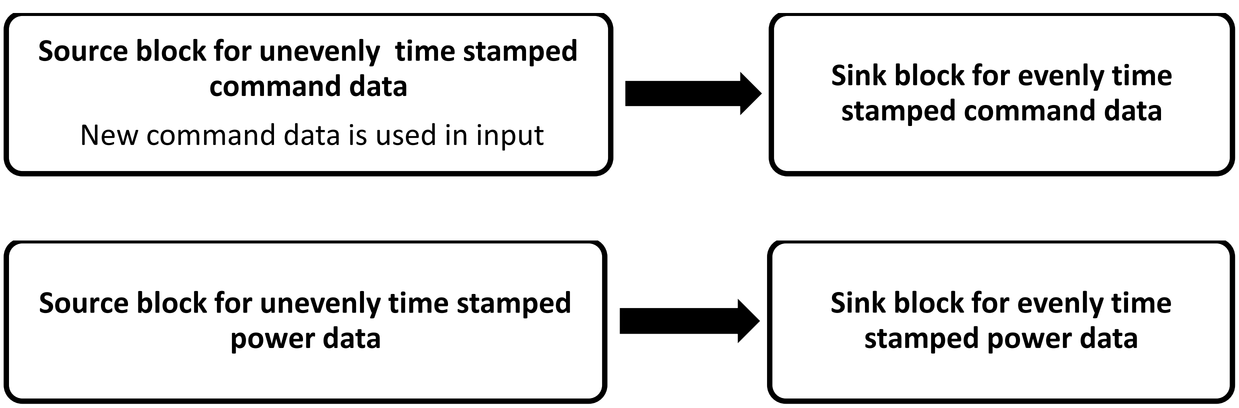


Figure 2.7 Block diagram of Simulink model used for data interpolation

Table 2.8 Modified command nomenclature for FortZED RDSI assets

Generation asset		
Command	**Operation**	**New command**
0	mod(Command, 12)	0
8704		4
8708		8
8710		10
Demand response asset		
Command	**Operation**	**New command**
0	mod(Command, 12)	0
2		2
66		6

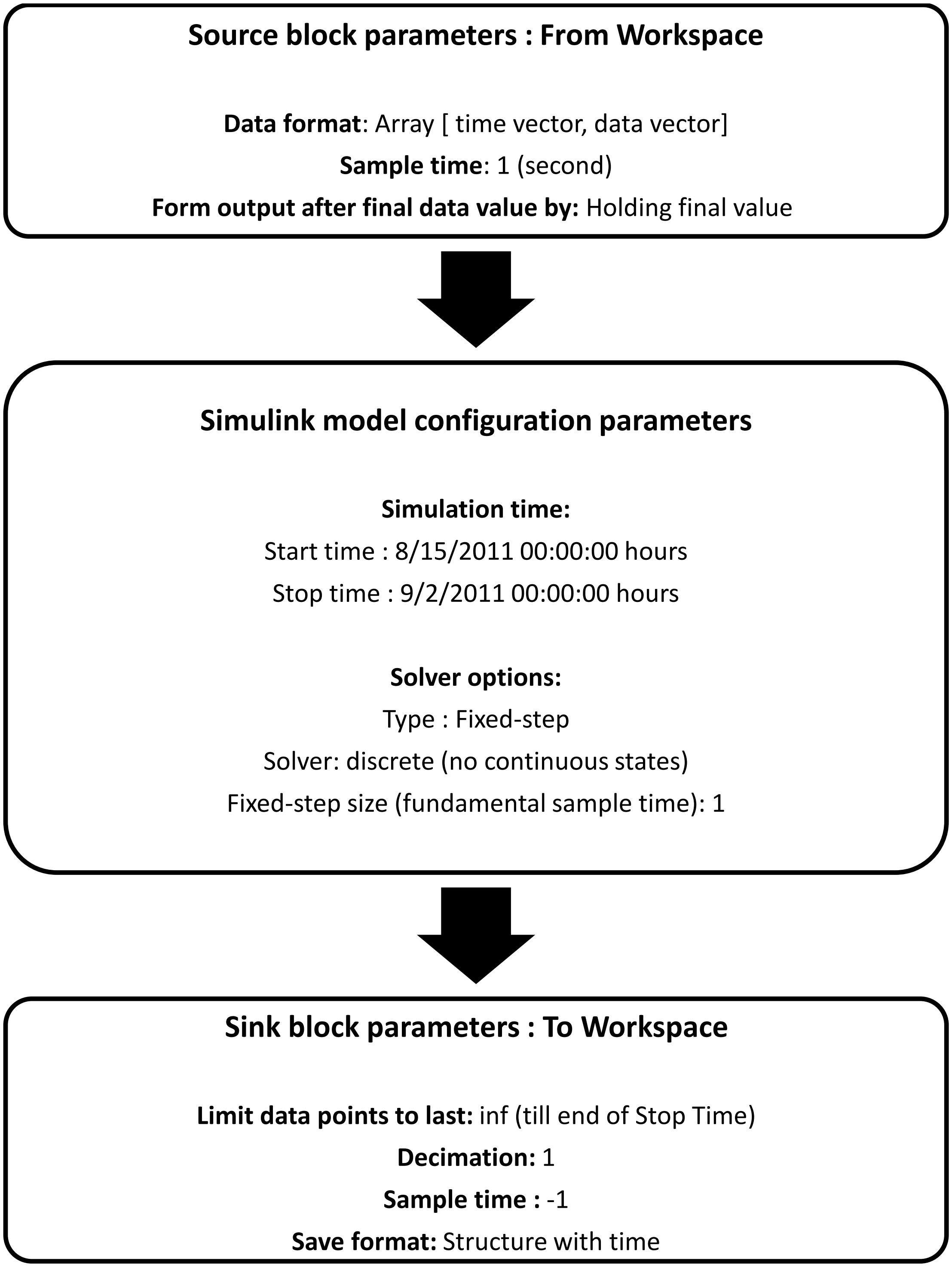


Figure 2.14 Block diagram of Simulink model parameters.

Another issue with the quality of data was the excursion points in power output values. Some of the assets had power value outputs reaching over the rating of the asset. Table 2.8 shows the asset values distribution in percent of asset rating for the third period of demonstration (August 15, 2011-September1, 2011).

The asset ratings for generation type assets were taken as per the nameplate ratings of machines or solar PV grid installations. The ratings of demand response assets were taken as the values committed by any participating site that would be available for operation when called by the microgrid controller. The power data output for generation assets greater than 110 % of rating was identified by thresholding and removed from the data set for further analysis.

The values were retained for the demand response assets and analysis done on the original data set. In some of the cases there was a large percentage of data point excursions. This deviation from commanded values and committed asset values for demand response can be attributed to data acquisition error, low controllability, probable human intervention, and interface issues of control system to building automation systems.

Although most of these deviations can be quantified, the reasons for the same are difficult to track without a more detailed knowledge and measurements at the demand response sites. Since, this demonstration exhibits a real-world scenario of the problems that might appear during an actual set up of a commercial microgrid, potential proactive measures such as additional instrumentation and a better interface between central controller and building automation systems for better controllability of assets may be taken.

Table 2.9 Power output distribution as percent of rating of asset

Asset name (identifier)	0-100 % of rating (% of dataset)	100-110 % of rating (% of dataset)	>110 % of rating (% of dataset)	Rating (kW)	Maximum Output (kW)
cfc Gen01	91.14	8.86	0.00	291.00	316.00
cfc Ldf01	100.00	0.00	0.00	29.00	28.00
cfc Ldf02	83.45	1.29	15.26	67.00	112.00
cfc Ldf03	99.19	0.00	0.81	11.00	18.00
cfc Ldf04	99.95	0.00	0.05	52.00	60.00
cfc Ldf05	100.00	0.00	0.00	16.00	15.00
cfc Ldf06	36.78	2.30	60.92	46.00	166.00
cfc Ldf07	95.69	0.00	4.31	20.00	60.00
cfc Pv01	99.93	0.00	0.07	5.00	6.00
cfc Pv02	100.00	0.00	0.00	51.00	51.00
csu Gen01	99.87	0.13	0.00	24.00	26.00
csu Gen02	100.00	0.00	0.00	114.00	55.00
csu Gen04	100.00	0.00	0.00	700.00	347.00
csu Ldf01	50.87	25.95	23.19	191.00	268.00
csu Ldf02	100.00	0.00	0.00	83.00	0.00
csu Ldf03	100.00	0.00	0.00	22.00	0.00
csu Pv03	99.99	0.01	0.00	17.00	18.00

Asset name (identifier)	0-100 % of rating (% of dataset)	100-110 % of rating (% of dataset)	>110 % of rating (% of dataset)	Rating (kW)	Maximum Output (kW)
eecl Gen01	94.95	5.05	0.00	228.00	247.00
eecl Gen02	100.00	0.00	0.00	260.00	233.00
eecl Gen03	100.00	0.00	0.00	10.00	0.00
eecl Gen04	100.00	0.00	0.00	20.00	0.00
eecl Gen05	100.00	0.00	0.00	350.00	218.00
eecl Gen06	100.00	0.00	0.00	140.00	0.00
int Gen02	93.71	6.10	0.18	59.00	72.00
int Gen03	83.34	16.66	0.00	59.00	62.00
int Gen04	100.00	0.00	0.00	100.00	92.00
lar Ldf01	50.33	0.00	49.67	1.50	7.00
lar Pv01	100.00	0.00	0.00	26.82	24.00
nbb Gen01	70.80	29.20	0.00	522.00	550.00
nbb Gen02	99.81	0.19	0.00	292.00	320.00
nbb Ldf01	99.99	0.00	0.01	85.00	861.00
nbb Ldf02	51.10	0.00	48.90	52.00	85.00
nbb Ldf03	100.00	0.00	0.00	150.00	146.00
nbb Pv01	99.80	0.15	0.05	200.00	249.00

2.5 Extracting test run period data

The duration of test runs varied on each day of the demonstration period depending upon the feeder load and load set point for the RDSI microgrid system. The load set points for each test run day are shown in Table 2.9. When the feeder load reached the set point, the RDSI system started dispatching based on an algorithm designed by one of the participating sites that hosted the control center for the microgrid. Since, the data obtained through interpolation in previous steps through the sample and hold model was sampled continuously for the performance period extending from midnight (00:00:00 Hours) of August 15, 2011 to the midnight (00:00:00 Hours) of September 02, it also included the period when the system was not in service. For proper characterization of the performance of the microgrid, analysis had to be performed only on the data corresponding to the run time period of FortZED RDSI system. The start and the end times for each of the days in the test run were obtained through RDSI project communication reports [2.10]. The useful data corresponding to these time vectors were extracted from bulk data set using the logical vector indexing in MATLAB®. Logical vector indexing helps in obtaining data corresponding to indices which are conditionally either logically true or false. This reduced the size of the data set from sampled set spanning 432 hours (i.e. 18 days, August 15, 2011 to September 1, 2011) to approximately 50 hours, retaining only test run period data for analysis. The power and command vector time stamps were retained for all the assets. The new dataset obtained was 11.92% in size of the sampled data set. Therefore, a large reduction in data to be handled was obtained.

The data plots shown in Figures 2.9 and 2.10 in red color are for all three test periods the following months in 2011, i.e. Period1:June13-June24, Period2: July18-July29, Period3: August15 – September1. Figure 2.9 shows the original power output data for asset *eeclGen01* and the sampled data plotted for the same asset at time stamps corresponding to times where power data occurs in original data set, shown in blue color.

Table 2.10 Control set points for test phase 3 runs

S.no.	Test run date	Set point (MW)
1	August 15, 2011	13.8
2	August 17, 2011	14.0
3	August 18, 2011	14.2
4	August 22, 2011	14.5
5	August 23, 2011	14.9
6	August 24, 2011	14.0
7	August 25, 2011	14.0
8	August 26, 2011	14.0
9	August 29, 2011	6.6
10	August 30, 2011	6.4
11	August 31, 2011	5.9
12	September 1,2011	6.3

Figure 2.10 shows the original power output data in red color for the asset *eeclGen01* and data set with power outputs corresponding to just the third period of test runs. Figure 2.10 is a magnified view of data points inside the region circled green in Figure 2.10. This was done for better spatial visibility of power output values for both data sets. Since, the data was sampled only for the time period corresponding to the test run spanning August 15, 2011 to September 1,

2011, the sampled and reduced data, shown in blue, occurs only in far right of the plots shown in Figures 2.9 and 2.7.

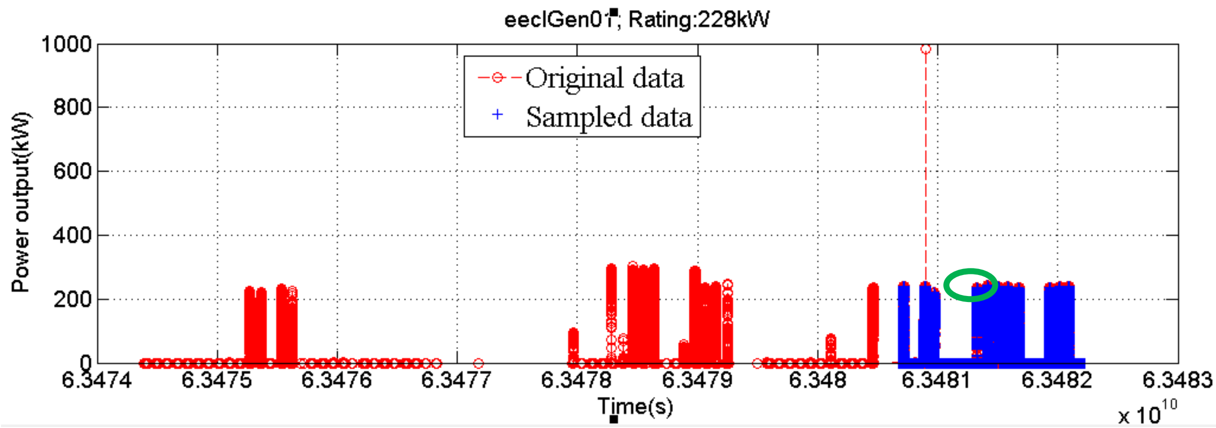


Figure 2.9 Original and sampled data for asset *eeclGen01*

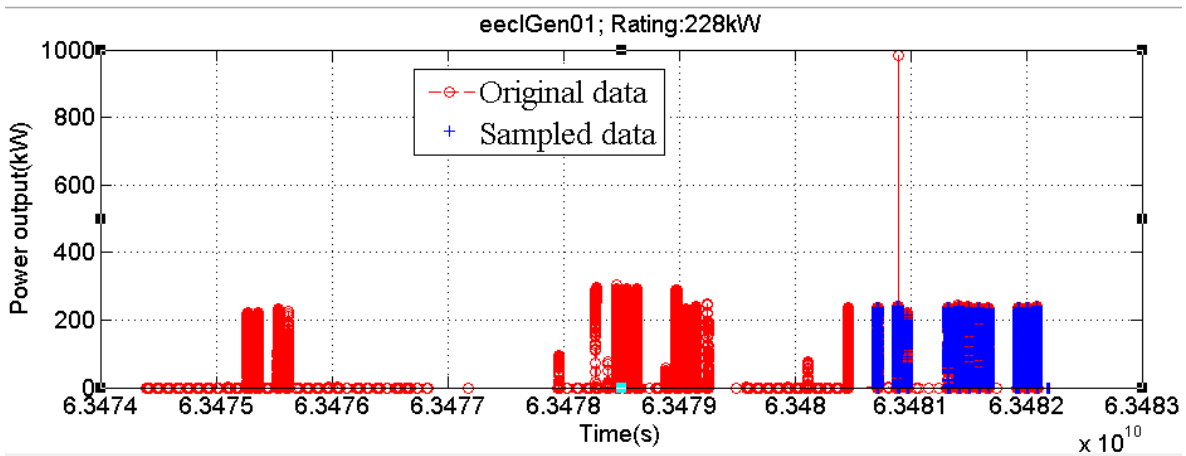


Figure 2.10 Original and reduced data for asset *eeclGen01*

These figures are for asset *eeclGen01*. It can be seen from the plots in Figure 2.11 that sampled data is present at each time sample and is held to previous value till a new data point occurs in original dataset.

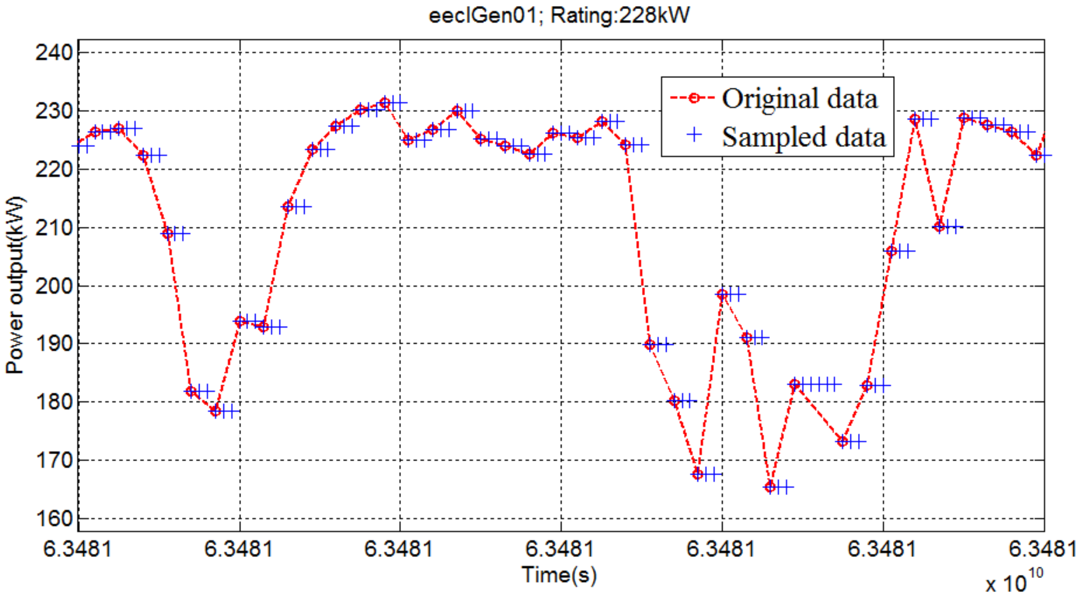


Figure 2.11 Magnified views of the original and reduced data for asset *eeclGen01*

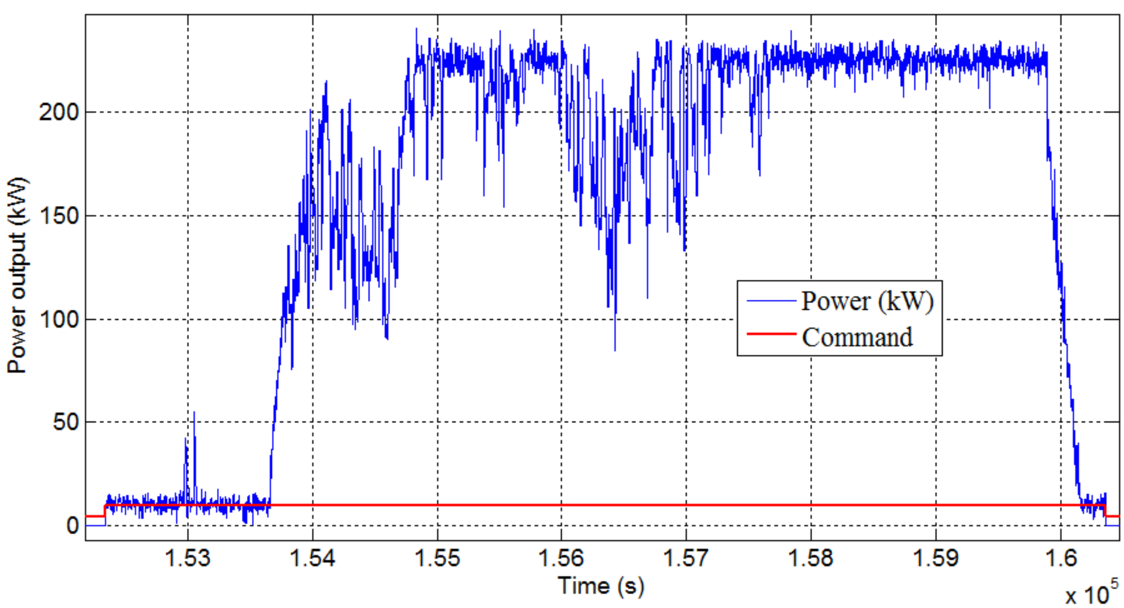


Figure 2.12 Command and power output values in time.

Extracted from reduced data set of command and power values for *eeclGen01* for a portion third phase of test runs, Figure 2.18 shows a plot of the command signal and the power output for one of the assets. The figure is illustrative of starting and stopping of a generator and is presented to show the asset response with commands for *eeclGen01* which was a conventional generator. It may be observed that the command changes initiate the start, ramping and stopping of the asset. The time resolution for sampled data is one second. It may also be observed that the time period spans about 70,000 seconds i.e., 2.7 hours (approximately) which is the amount of time this asset ran for the initiated command. Since, the assets were not called twice in a test run day, this run duration is for the particular test run day.

The run time period data was stored in a separate data set structure and a few fields representing the name of the asset, a description, the type, and the rating were added for possible use in further analysis. The asset name and the description were string fields in substructures. Rating for generation assets was the machine nameplate value in kW and that for the load shedding assets was the value available in kW. The type of asset was an integer identifier for selection during analysis of group of assets based on its nature of being a generation or DR type. Generation assets were allocated '1' as an identifier and all other assets were allocated '0'. Availability information for the assets, resolved at one second, was also added at the substructure levels with '1' denoting availability and '0' denoting unavailability.

At this point the data set was sufficiently reduced and contained information to perform further analysis, calculate metrics, and derive asset behavior information during the test runs which is presented in Chapter 3 of this work. The MATLAB scripts and models can be obtained from the supplementary documents provided with the thesis.

REFERENCES:

[2.1] M. Panwar , G.P. Duggan, R.T. Griffin, S. Suryanarayanan, D. Zimmerle, M. Pool, S. Brunner, ”Dispatch in microgrids: Lessons from the Fort Collins Renewable and Distributed Systems Integration demonstration project”, *The Electricity Journal* (Article in Press)[Online], Available, http://dx.doi.org/10.1016/j.tej.2012.09.011

[2.2] Spirae Inc. website, [Online], Available, http://www.spirae.com/ Last accessed 10/10/12

[2.3] Brendle Group website, [Online], Available, http://www.brendlegroup.com/ Last accessed 10/10/12

[2.4] Woodward Inc. website, [Online], Available, http://www.woodward.com/, Last accessed 10/10/12

[2.5] Advanced Energy website, [Online], Available, http://www.advanced-energy.com/, Last accessed 10/10/12

[2.6] Eaton Corporation website, [Online], Available, http://www.eaton.com/Eaton/index.htm, Last accessed 10/10/12

[2.7] VanDyne Inc., website, [Online], Available, http://www.vandynesuperturbo.com/, Last accessed 10/10/12

[2.8] ‘RDSI Demonstration Test Run Data’, email communications with J. Price dated 9/28/2011

[2.9] NERC Generating Unit Statistical Brochure, October 2008. http://www.nerc.com/page.php?cid=4%7C43%7C4 Accessed 8/14/2012.

[2.10] 'RDSI trend capture and peak reduction reports', RDSI SiteShare portal for RDSI Project Group.

Chapter – 3

Data analysis and reliability metrics

This chapter describes the methodology adopted to calculate some performance metrics for microgrid. Algorithms are also presented for clarifying the process of data analysis for the same.

IEEE standard 493-2007 defines reliability as the ability of a component or system to perform required functions under stated conditions for a stated period of time. The term reliability is also used as reliability characteristic (metric) denoting probability of success or a success ratio. In general usage, reliability refers to system performance over time [3.1].

In purview of electric power systems, reliability can be defined as the uninterrupted availability of electric power at a certain acceptable standard of power quality. Power acceptability also plays a major role when defining power system reliability. It is defined as the minimum acceptable power quality, and seems more appropriate from the perspective of the end-user (customer) [3.2]. For the power producer and system operator, reliability defines the performance and desired objective precisely. Non-interruption, low harmonics, low deviations from acceptable levels of voltage and frequency, and non-flicker are some of the desired characteristics of good power quality [3.3]. These are quantified and used as benchmarks or standards such as IEEE 519-1992, for supplying power to the customer [3.4]. Power system reliability is one of the primary quantification measures for the performance of a power system. Certain reliability metrics have been promulgated as per the standards created for power system operation and power delivery. NERC metrics are used to define the performance of an electric power system in North America. In this chapter, some of the metrics for the FortZED RDSI demonstration data as per the NERC criteria are provided. Since the original data set contained only the time stamped power output and command value information, only those NERC metrics requiring only this information have been calculated. A few other metrics, which need additional information, have not been calculated in this chapter. This chapter also provides information on the need and development of a new reliability metric for the design and operation of microgrids called the *microgrid peak reserve ratio*.

3.1 Data Analysis - Introduction

The data set obtained after data reduction, as shown in Chapter 2, contains power and command information that is evenly time stamped at one second. This data is also reduced to only the run time periods. Start and end times for test runs are given in Table 3.1. Additional information such as the identifier (name), rating, type and the availability of the asset is also added for further analysis.

Table 3.1 Test run start and end times for each day in phase 3 of test runs

S.no.	Test run date	Start time (hh:mm)	End time (hh:mm)
1	August 15, 2011	11:00	14:15
2	August 17, 2011	11:37	16:02
3	August 18, 2011	10:30	13:08
4	August 22, 2011	11:38	17:44
5	August 23, 2011	13:59	17:11
6	August 24, 2011	14:01	17:49
7	August 25, 2011	14:00	17:30

S.no.	Test run date	Start time (hh:mm)	End time (hh:mm)
8	August 26, 2011	14:05	17:06
9	August 29, 2011	08:16	17:03
10	August 30, 2011	10:25	14:02
11	August 31, 2011	09:26	12:35
12	September 1,2011	10:15	16:15

Asset name and description were added as string fields in substructures. Rating for generation assets was the machine nameplate value in kW. For load shedding assets the rating was the available capacity in kW for load shedding. Type of asset is an integer identifier for asset selection during analysis of group of assets based on its nature of being a generation or DR type. Generation assets were allocated '1' as identifiers and all other assets were allocated '0'. Availability information for the assets was also added at substructure levels. Availability was also at resolved one second with '1' denoting availability and '0' denoting non-availability.

More fields were added to support metric calculations. The information of an asset being in service was also added as a binary value, with a resolution of one second such that a '1' denoted an in-service state, and a '0' denoted a not in-service state. These values were obtained as logical vectors by comparing the power output in time with the capacity threshold which was statistically calculated for each asset.

3.2 Data Analysis - NERC metrics

NERC is the electric reliability organization (ERO) certified by the Federal Energy Regulatory Commission (FERC) to establish and enforce reliability standards for the bulk power system. The main functions of NERC are:

- Development and enforcement of reliability standards
- Assessment of generation adequacy annually via a ten-year load forecast, and summer and winter load forecasts;
- Monitoring the bulk power system, and,
- Education, training, and certification of the utility industry personnel [3.5], [3.1].

NERC also specifies metrics for electric power system reliability. The mathematical equations used for calculating the metrics are given in the NERC Generating Unit Statistical Brochure [3.6]. The relevant NERC metrics calculated for RDSI test run data are listed below:

3.2.1 Starting Reliability (SR) ,

3.2.2 Availability Factor (AF) ,

3.2.3 Average Run Time (ART) ,

3.2.4 Service Factor (SF) ,

3.2.5 Net Capacity Factor (NCF) ,

3.2.6 Net Output Factor (NOF) ,

3.2.7 Weighted Service Factor (WSF) , and

3.2.8 Weighted Availability Factor (WAF).

The definition of each of the metrics mentioned above is presented with a detailed explanation of the process of information extraction for calculation of the metrics in the following subsections.

3.2.1 Starting Reliability

Starting Reliability is given by formula shown in (3.1):

$$\mathrm{SR} = \frac{\text{Actual Unit Starts}}{\text{Attempted Unit starts}} * 100\ (\%)\ . \tag{3.1}$$

NERC definitions:

Actual Unit Starts: Number of times the unit was synchronized to the transmission system.

Attempted Unit Starts: Number of attempts to bring the unit from shutdown to synchronization.

Calculation methodology:

Asset threshold capacity is the minimum value of power output for any asset which when exceeded after the start command is issued within response monitoring time for that asset, the asset is said to have started successfully. The asset threshold capacity was determined statistically for each asset from the test run data. Figure 3.1 shows the histograms for asset *nbbGen02* for calculation of asset threshold capacity.

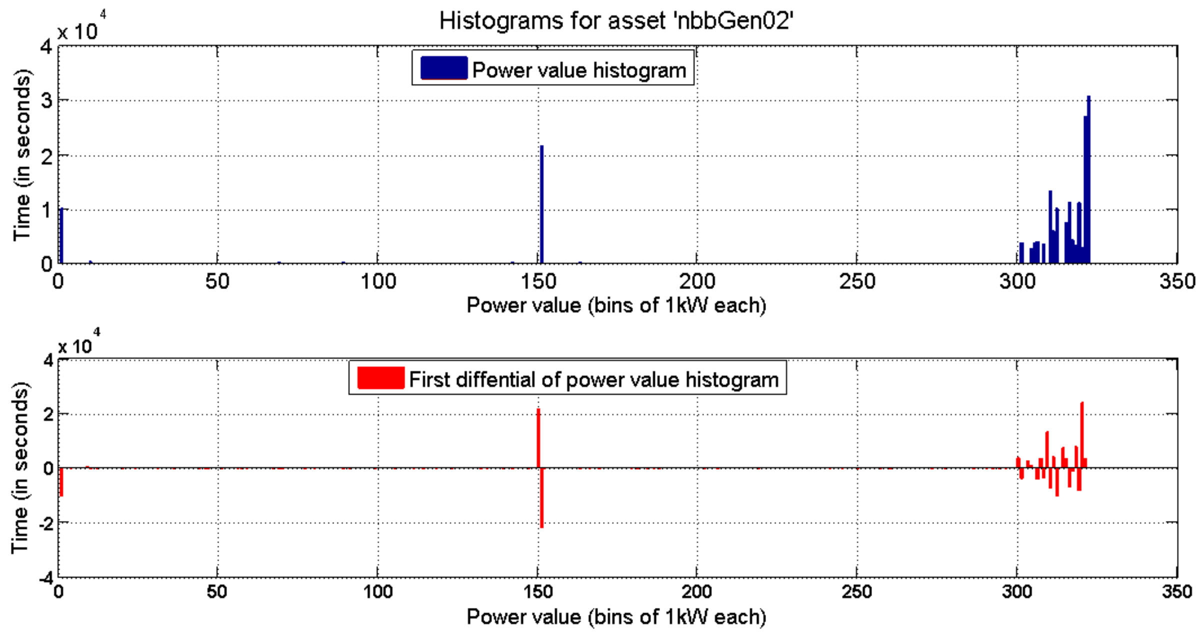


Figure 3.1 Histograms for asset threshold calculation, example of *nbbGen02*.

The histogram count is obtained in MATLAB® and this gives the count of the number of seconds the asset power output lies in each bin. The bin size is set to be '1' which is equal to the dead band on power output variation. Thus, it can be seen from the upper plot in Figure 3.1, the asset stays most of the times in zero or near asset rating value, i.e. it either stays off or at rated load. The spikes near 150th bin represents transition phase from low load to rated load. Now, the first differential of the above histogram counts is found. This represents the change of state of asset from one bin to the adjacent one. A negative change represents that asset stays more in previous state than in present one or simply increasing ramping rate while a positive change suggests vice versa, i.e. decreasing ramping rate. The lower valued bins have a negative change. This is used to find the bin or the power output of asset where the change becomes positive after the asset leaves the state where it is not in service. The negative differential index just after this positive differential index is the bin at which the asset ramps to a higher value. Since each bin is equal to 1kW, this index directly gives the power value above which asset can be considered to be in service. This is the asset threshold capacity for that asset. The values for each asset are shown in Table 3.2.

The response monitoring time (RMT) for each asset is also mentioned. The response of the asset was determined based on the capacity of the asset and is given by the (3.2) below. These values were obtained from the control system summary document used for asset dispatch [3.7].

$$\begin{aligned} \text{Response monitoring time} &= 180\ \text{s, if asset rating} \leq 250\text{kW} \\ &= 360\ \text{s, if asset rating} > 250\text{kW}. \end{aligned} \tag{3.2}$$

The response monitoring time is not applicable to solar photovoltaic sources as they were the un-controllable generation assets in the FortZED.

Table 3.2 Threshold capacity values for assets in FortZED RDSI.

Asset name	**Rating of asset (kW)**	**Threshold capacity (kW)**	**Response monitoring time (s)**
cfc Gen01	291.00	137	360
cfc Ldf01	29.00	0	180
cfc Ldf02	67.00	130	180
cfc Ldf03	11.00	84	180
cfc Ldf04	52.00	0	180
cfc Ldf05	16.00	29	180
cfc Ldf06	46.00	9	180

Asset name	Rating of asset (kW)	Threshold capacity (kW)	Response monitoring time (s)
cfc Ldf07	20.00	0	180
cfc Pv01	5.00	0	Not Applicable
cfc Pv02	51.00	0	Not Applicable
csu Gen01	24.00	0	180
csu Gen02	114.00	8	180
csu Gen04	700.00	3	360
csu Ldf01	191.00	11	180
csu Ldf02	83.00	11	180
csu Ldf03	22.00	49	180
csu Pv03	17.00	5	Not Applicable
eecl Gen01	228.00	5	180
eecl Gen02	260.00	10	360
eecl Gen03	10.00	0	180
eecl Gen04	20.00	3	180
eecl Gen05	350.00	8	360
eecl Gen06	140.00	4	180
int Gen02	59.00	4	180
int Gen03	59.00	0	180
int Gen04	100.00	11	180
lar Ldf01	1.50	0	180

Asset name	Rating of asset (kW)	Threshold capacity (kW)	Response monitoring time (s)
lar Pv01	26.82	0	Not Applicable
nbb Gen01	522.00	2	360
nbb Gen02	292.00	10	360
nbb Ldf01	85.00	4	180
nbb Ldf02	52.00	31	180
nbb Ldf03	150.00	151	180
nbb Pv01	200.00	5	Not Applicable

Actual Unit Starts: The number of times the asset achieved successful start by producing a power output above the asset threshold capacity within a specified amount of time when a control command was issued to operate at either the base load or maximum load rating for a generation type asset and committed load shed value when called to shed load.

Attempted Unit Starts: The number of times a control command corresponding to either the base rating of asset or the maximum rating of asset operation was issued by the control system. Both these values correspond to rating of asset and are treated identically when calculating attempted unit starts. Both values of commands are considered differently for completeness. The results would not be affected in this particular calculation of unit starts because the threshold for comparison is the asset threshold capacity and is below the rating of the asset. The control commands for the base load and the maximum rated capacity were ‘4’ and ‘10’ for generation type assets. For load shedding assets, a single control command ‘6’ was issued to shed load and

‘0’, ‘2’ were for bringing the asset to the state of operation in which it was before the control command was issued. Thus, load shedding asset commands were analogous to an ON-OFF type control. To detect the commands in time, the change in command state was determined. Since, the change of 4, 6, 8 or 10 corresponded to a command issued for a generator start or load shed, this feature was exploited to obtain the time points where a start command was issued. This is presented in Table 3.3 and as a state diagram in Figure 3.2.

Table 3.3 Command change pattern for generation and DR type assets.

Generation type asset			
Command(t) : OFF	**Command(t+1) : ON**	**Command change(t+1)**	**Action**
0	8	8	BASELOAD
0	10	10	MAX LOAD
4	8	4	BASE LOAD
4	10	6	MAX LOAD
Demand response type asset			
0	6	6	SHED LOAD
2	6	4	SHED LOAD

Next step was to determine asset start response within response monitoring time. The response time varied for an asset based on the rated capacity. Since the control system took this into account, the rated capacity of asset must also be considered when calculating the command response of an asset. Figure 3.3 below shows an illustration for checking a unit start. A command

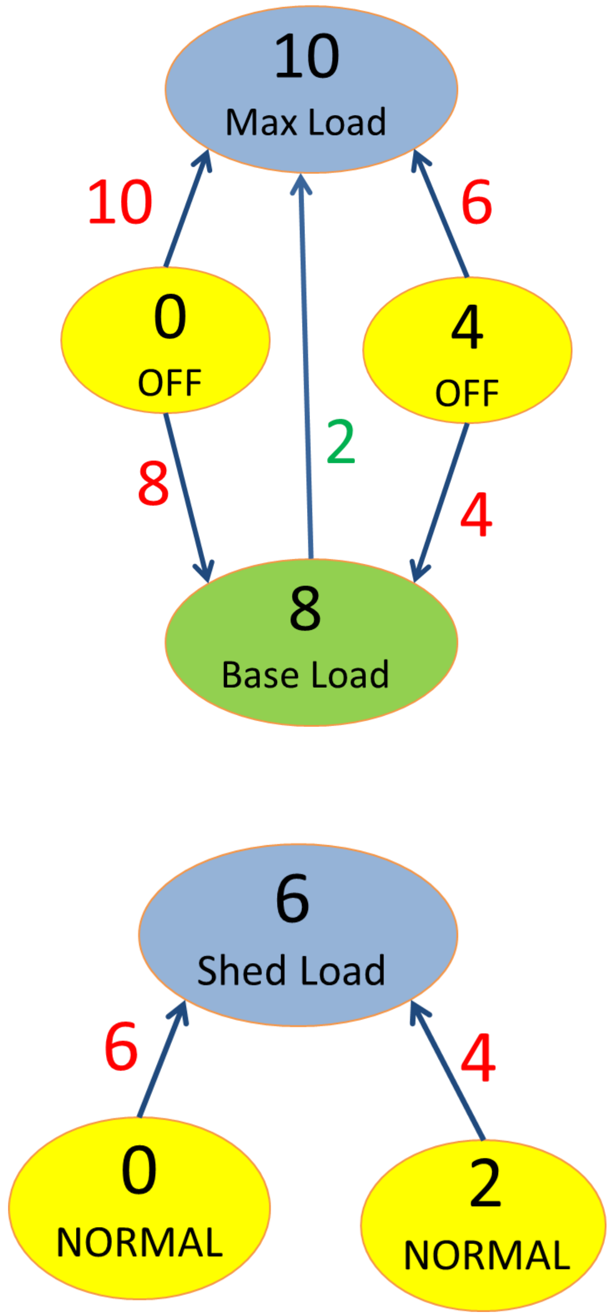


Figure 3.2 Command change state diagram for generation and DR assets

value vector, command change vector and index vector are shown to have a change in command at C1, C2 and C3. The vector length to be scanned is determined using RMT.

The following procedure was followed for observing the start of an asset from the data gathered:

1. The time index at which a command change occurred was obtained by scanning the data for each asset in time.
2. When all such points were obtained, the response was observed for the first index where command change occurred.
3. Output of the asset was monitored for next the 180 or 360 seconds depending upon rating of the asset.

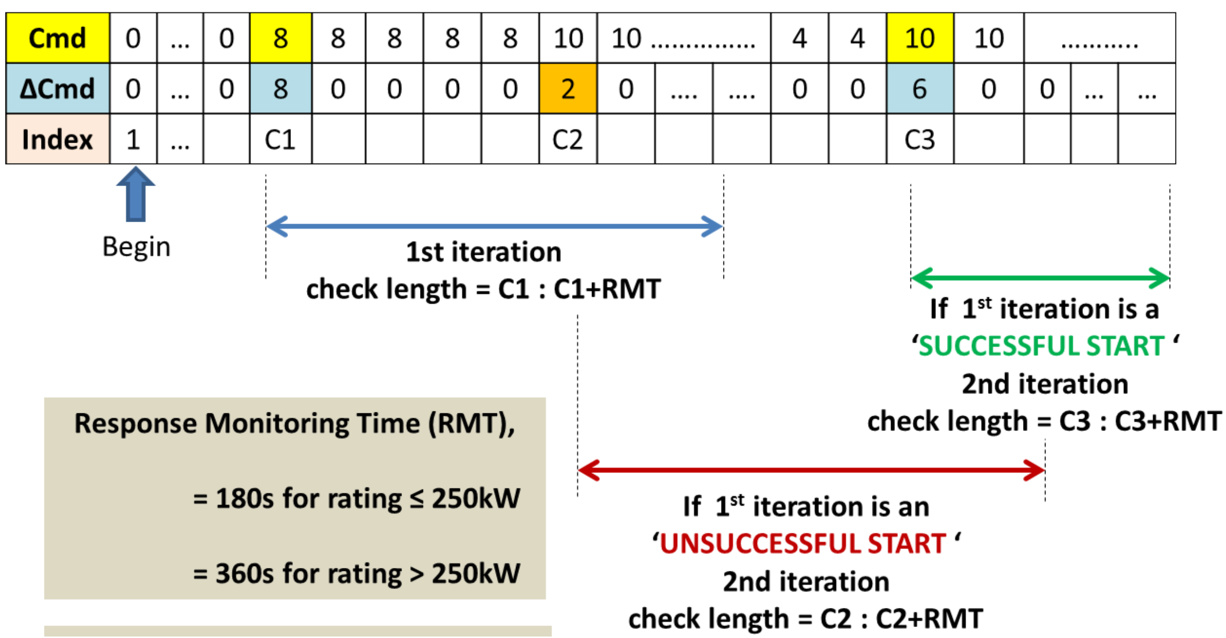


Figure 3.3 Illustration of checking vectors for successful start

4. If a start occurred, i.e. power output crossed the threshold capacity; the asset was registered to have started successfully. In this case, the next search started at an index where a command change occurred after 180 or 360 seconds of the previous

command change. Any start command change index was not considered if it fell within the response monitoring time of the asset for the previous command.

5. If the asset power output did not cross the threshold, the asset was registered to have failed to start and the search moved to the next index where the command change occurred, irrespective of whether the command change occurred within the response monitoring time of asset.
6. The process was repeated as stated in steps 3-5 until the end of data set occurred.
7. Since there was a possibility that end of the data set may have a successful start which may lie within the final 180 or 360 seconds of the data set, the length for response monitoring time was programmed to choose the minimum of the following two: a) the length of the response monitoring time based on the asset rating, or, b) the length of the remaining data set on each iteration for checking the power output. Thus, the data set was scanned till the final data point present and the maximum possible information was extracted.

The flow chart in Figure 3.4 explains the above process of successful start identification. Also, for conventional generators in FortZED RDSI, 41 start attempts were detected and 31 successful asset starts were calculated for 14 generators, thereby giving an aggregate starting reliability of 70.45% for generators.

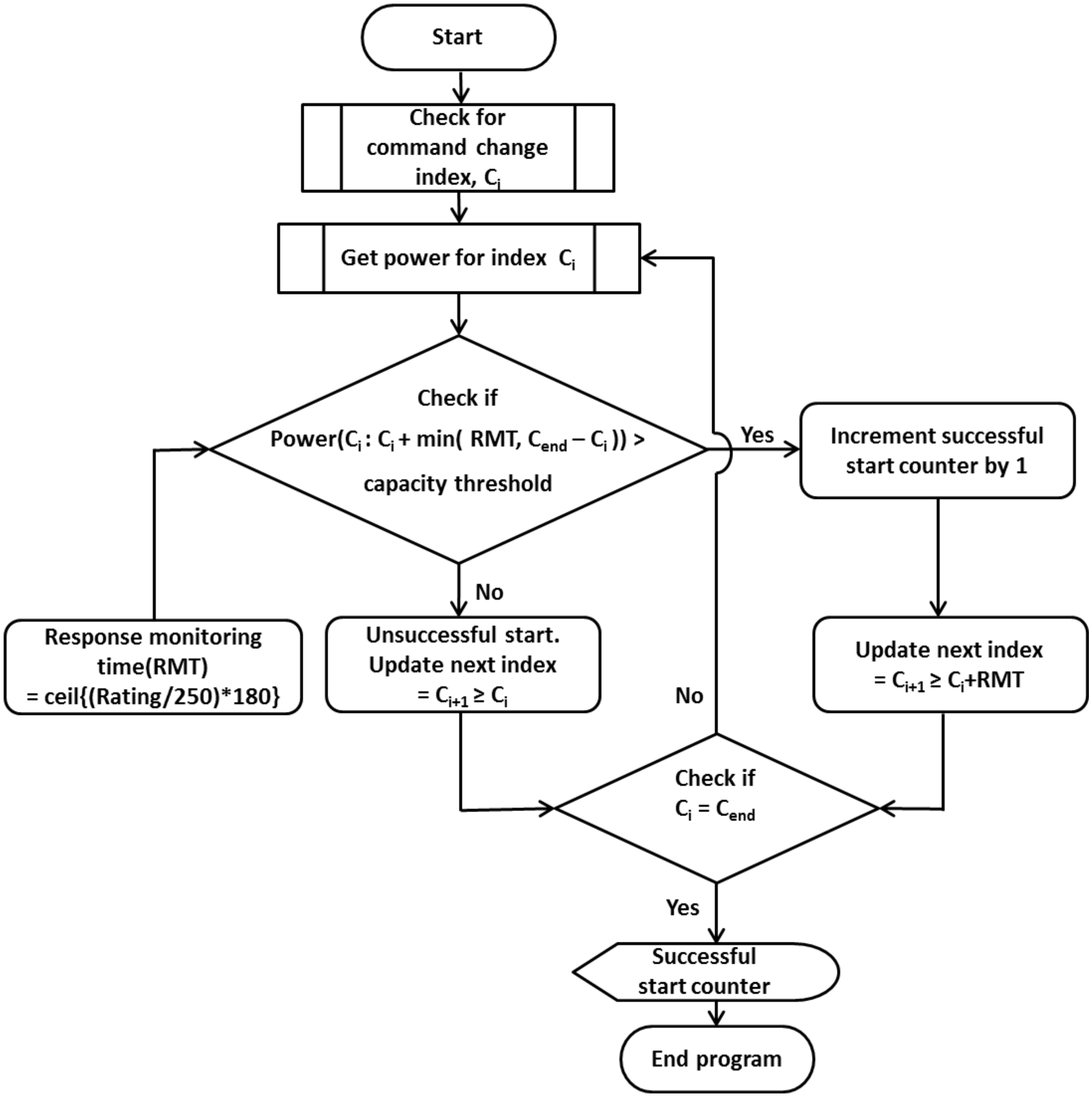


Figure 3.4 Flow chart for algorithm used to identify successful start of an asset

3.2.2 Availability Factor

Equation (3.3) describes the Availability Factor as

$$\mathrm{AF} = \frac{\text{Available Hours}}{\text{Period Hours}} * 100\ (\%)\ . \tag{3.3}$$

NERC definitions:

Available Hours (AH): Sum of service hours, reserve service hours, pumping hours and synchronous condensing hours (for conventional generators).

Period Hours (PH): Number of hours (in a calendar year) a unit was in active state. A unit generally enters the active state on its commercial date (date when commercial operation starts).

Calculation methodology:

Available Hours (AH): The number of hours of the test run period when asset was not unavailable. All assets are considered to be available until any asset is declared unavailable for participation in test runs.

Period Hours (PH): The asset availability information is already contained in the RDSI FortZED data structure for each time instant and this corresponds to the total third test run period.

3.2.3 Average Run Time

Average Run Time is the run time in hours per successful unit start as shown in (3.4)

$$\mathrm{ART} = \frac{\text{Service Hours}}{\text{Actual Unit Starts}} \tag{3.4}$$

NERC definitions:

Service Hours (SH): Total number of hours a unit was electrically connected to the transmission system.

Calculation methodology:

Service Hours (SH): The number of hours the asset was delivering power over the capacity threshold. The data is sampled at one second, which was then converted to hours.

3.2.4 Service Factor

Service Factor is an important reliability metric and is given by (3.5) as:

$$\mathrm{SF} = \frac{\text{Service Hours}}{\text{Period Hours}} * 100\ (\%)\ . \tag{3.5}$$

3.2.5 Net Capacity Factor

Net Capacity Factor is another metric for power system performance quantification. It takes into consideration the rating of the asset and is given by (3.6):

$$\mathrm{NCF} = \frac{\text{Net Actual Generation}}{\text{Period Hours} * \text{Net Maximum Capacity}} * 100\ (\%)\ . \tag{3.6}$$

NERC definitions:

Net Actual Generation (NAG): Net electrical energy produced by the unit during the period being considered.

Net Maximum Capacity (NMC): Capacity a unit can sustain over a specified period when not restricted by ambient conditions or equipment derating, minus the losses associated with station service or auxiliary loads.

Calculation methodology:

Net Actual Generation (NAG): It is the electrical energy output in MWh obtained by multiplying the average power output of the asset with the period hours or the test run period.

Net Maximum Capacity (NMC): Since no other information is available related to load losses, the rating of the asset is considered as the NMC.

3.2.6 Net Output Factor

Net Output Factor is given by (3.7) as:

$$\mathrm{NOF} = \frac{\text{Net Actual Generation}}{\text{Service Hours} * \text{Net Maximum Capacity}} * 100\ (\%). \qquad (3.7)$$

3.2.7 Weighted Service Factor

Weighted Service Factor is a capacity weighted metric that takes into consideration the asset capacity, thus giving a better quantitative representation of the service factor of a group of assets as shown in (3.8):

$$\mathrm{WSF} = \frac{\sum(\text{Service Hours} * \text{Net Actual Generation})}{\sum(\textit{Period Hours} * \text{Net Maximum Capacity})} * 100\ (\%)\ . \qquad (3.8)$$

3.2.8 Weighted Availability Factor

Weighted Availability Factor is a capacity weighted metric that takes into consideration the asset capacity, thus giving a better quantitative representation of the availability factor of a group of assets and is given by (3.9):

$$\mathrm{WAF} = \frac{\sum(\text{Available Hours} * \text{Net Actual Generation})}{\sum(\textit{Period Hours} * \text{Net Maximum Capacity})} * 100\ (\%). \qquad (3.9)$$

3.3 Other performance metrics and feeder level data analysis

Two more performance metrics were developed and calculated for the microgrid system which gives useful information about operation, utilization and planning for microgrids. All the metrics presented before this was as per NERC and were reflective of bulk power system reliability. The two metrics developed and presented are reflective of microgrid system both in parallel with the bulk power system and in islanded operation. The basis for these metrics was the analysis of the aggregated output of the microgrid, contribution of assets in the microgrid, the spinning and non-spinning reserves during test runs.

3.3.1 Peak Reserve Ratio

Peak reserve ratio (PRR) is a time-based performance metric which provides information on the microgrid reserve capacity, as a system reserve capacity, during periods of system peak demand when the microgrid is operating connected to the bulk power system. The metric is given by (3.10):

$$\mathrm{PRR} = \frac{\mathrm{Microgrid\ Reserve(t)}}{\mathrm{Total\ Feeder\ Load(t)}}$$

$$= \frac{\mathrm{Microgrid\ Capacity(t)} - \mathrm{Microgrid\ Output(t)}}{\mathrm{Net\ Feeder\ Load(t)} + \mathrm{Microgrid\ Output(t)}} \ (p.u.). \qquad (3.10)$$

It may be noted here that all the quantities are time-varying and hence attributing to the PRR metric a time-varying characteristic. Although the quantity 'Microgrid Capacity' may not change significantly in the short term i.e., days, but assigning the quantity a time characteristic ensures considering any change in the availability of microgrid. This inherent feature of the metric fetches more meaning even for a longer period of time. These metrics attempt to provide comprehensive information about the exact reserve available for dispatch.

The unit of PRR is per unit (p.u.). Thus, the units for all the input quantities must be uniform prior to calculating the metric. It may even be given as a percentage of the total feeder load. The PRR would be a vector with time-dependent values which may be used to observe the microgrid behavior in time or be further used to obtain information based on different periods of the microgrid operation by performing the desired operation such as averaging to obtain the metric value on a block-wise basis. The block here may be a window of fixed timespan like 5 minutes, 15 minutes, an hour, or several hours. The choice of a block size would again be dependent on a number of factors such as granularity of the information required, commercial value to user, market, and economic standards of the electric utility. Platte River Power Authority measures actual load during an hour based on 20 measurements every 3 minutes. The recorded load for that hour is the integrated total of these 20 readings [3.8].

For calculations for FortZED RDSI demonstration, the calculations are done for every second and this gives instantaneous values of reserve ratio. Now, the time instant when total feeder peak occurs, the PRR can be obtained. The calculations done with this method gives the worst case reserve ratio value which is congruent with total feeder peak. The data used here for calculating PRR is obtained from a data set of measurements made at feeder level during the FortZED RDSI test runs. This data set with feeder level measurements includes additional information of feeder-level power output along with the asset-level generation and demand response within the microgrid. The feeder level data is also unevenly time stamped and hence sampled at one-second resolution using the same principle as the asset level data discussed in Chapter 2.

3.3.2 Microgrid Peak Reserve Ratio

Microgrid peak reserve ratio (MPRR) is another time-based metric for gleaning information about microgrid reserve at periods when microgrid output peak occurs; however, this is different from PRR in that it is normalized over ‘Microgrid Capacity’, which is also a time-varying quantity in the long term. This metric assumes the role of ‘power system reserve’ if the microgrid operates in islanded mode. This metric can be used to obtain the internal reserve when considering microgrid to be a separate system, for planning, or monitoring purposes in both grid-connected and islanded modes. The plots in Figure 3.5 show the MPRR and other feeder level parameters for August 23, 2011. The plot here shows values for data sampled at 1 second. The test run duration is around 4 hours and MPRR touches a minimum of 0.5 p.u., i.e. almost 50% of the microgrid capacity stays as reserve at all times. Although, this may happen on a particular day, but over a longer period of time, such an operation may result in stranded assets and hence stranded investment. This may be avoided by planning the dispatch of assets in the microgrid by observing the trend over a chosen duration. The choice of time would depend on approach followed by the operator for planning based on historical trends. FCU measures the power demand for every 15 minutes in an hour, i.e. at 0, 15, 30, 45 clock minutes. The average of these 4 measured values of demand per hour gives the demand value for that hour. The peak hour for a month is obtained based on these hourly demand values and used for billing purposes. For purposes of calculation presented here for the FortZED RDSI demonstration runs, we adopt the methodology of calculating instantaneous reserve ratios for each day. The reserve value at the time instant when microgrid output peak occurs each day is called MPRR for that day.

$$\mathrm{MPRR} = \frac{\mathrm{Microgrid\ Reserve(t)}}{\mathrm{Microgrid\ Capacity(t)}}$$

$$= \frac{\mathrm{Microgrid\ Capacity(t)} - \mathrm{Microgrid\ Output(t)}}{\mathrm{Microgrid\ Output(t)}}\ (p.u.). \qquad (3.11)$$

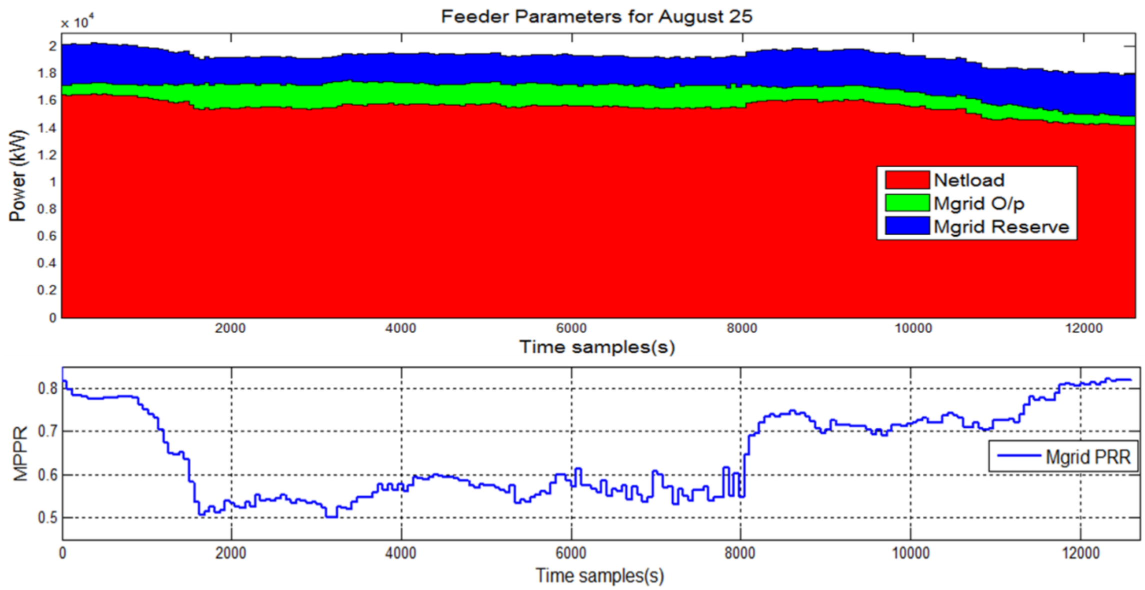


Figure 3.5 Feeder parameters and instantaneous MPRR for August 23, 2011

3.4 Peak Load Reduction

Since, the objective of the FortZED RDSI test runs was to reduce the feeder peak load by 20 - 30 % at the feeders, a few different ways of calculating the peak load reductions are presented in the section below. Similar to PRR and MPRR, PLR may also be expressed as time-varying metric and given by a percentage normalized over the total feeder load. But, a metric such as PLR calculated at a higher resolution, e.g. one-second, is informative but not worth the increased computational efforts. Instead, a more comprehensive result can be obtained using a bigger data set, e.g. using time blocks of 15 minutes, 60 minutes, or clock hour blocks.

$$\mathrm{PLR} = \frac{\mathrm{Microgrid\ Output(t)}}{\mathrm{Total\ Feeder\ Load(t)}} * 100 \ \ (\%). \tag{3.12}$$

The numerator and denominator in the calculation above are time congruent. The traditional approach followed by DOE is based on picking the numerator, i.e. microgrid output and denominator as total feeder load from the annual load curve [3.9]. The load curve is shown in Figure 3.6. But, such method results in loss of time congruency of peak load reduction. It can give an estimate or approximation of peak load reduction capability but is not accurate. It does not depict the load reduced when the feeder load peak occurred.

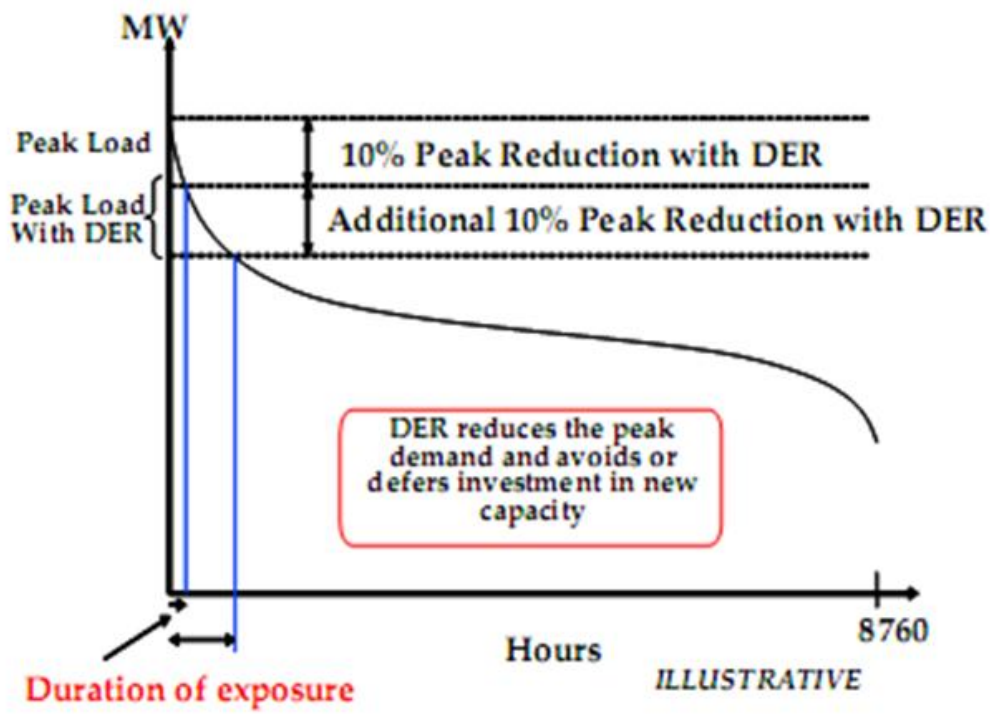


Figure 3.6 Illustrative load curve for a year for peak load reduction calculation (Image taken directly from [3.9])

Figure 3.6 shows the actual percent load reduction values calculated using two approaches: traditional and at time corresponding to total feeder peak. The difference in values can be clearly seen on all days except September 1, when the actual output of microgrid occurs at the time instant of maximum total feeder load. The values calculated at with time congruent values are conservative compared to the traditional approach but provide a more accurate assessment of actual peak load reduction at the instant when total feeder peak occurred. This is just one of the methods which can be used for calculations. Thus, four other alternative approaches are presented here.

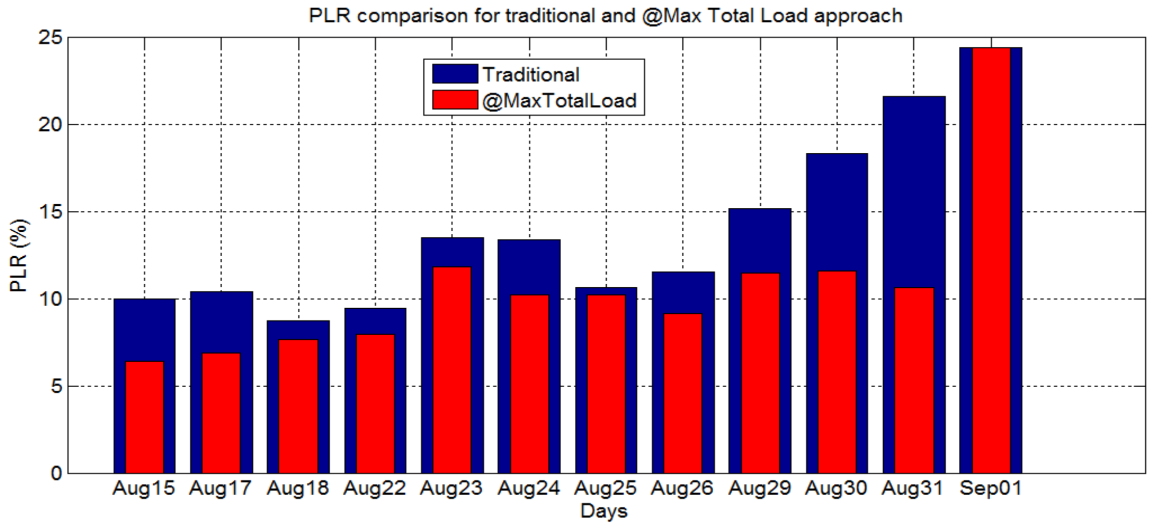


Figure 3.7 Comparison of percent peak load reduction calculations for the traditional approach and at time when total feeder peak occurs

For the purpose of exploring a few of the above mentioned choices of block sizing data, a one-hour time block is used to obtain data values for different clock hours. Different approaches for obtaining PLR values are discussed now. It may be noted here that clock hour refers to an hour between consecutive strikes of a clock. Any data considered in the h^{th} hour binds data between hours *h* and *h-1* and the data set may or may not be equal to one complete hour of data. For example, if a system is idle from 11:00 hours until it is engaged at 11:30 hours, then hour *h* =11 would contain 30 minutes worth of data in the hour block 11 – 12. This approach gives a single vector PRR for each hour block and, subsequently, a single scalar value may be obtained for each hour block. These hour block metrics may be referred to as PLR_h and is a slight modification of the time-based metric vector, PLR proposed above. Two approaches are given below in (3.13) and (3.14): The various approaches presented below compute the metrics over one clock hour blocks.

Approach-I: Mean

$$PLR_{mean} = \text{mean} (PLR_{hk}) \tag{3.13}$$

where h is the notation for the clock hour, k is the notation for k^{th} measurement for any hour h.

PLR_{mean} is the mean of all the measurements during each clock hour h, i.e. PLR_{h1}, PLR_{h2}, PLR_{h3}, ….. PLR_{hk}, and so on. So, each value of PLR_{mean} would be a vector of length h and each value would be mean of all the PLR values in that corresponding hour. This gives the average value of peak load reduction per clock hour. This may find importance when the peak load reduction value corresponding to a particular hour, for example the coincident peak hour, is to be picked.

Approach-II: Infinite norm

$$PLR_{inf} = \text{norm} (PLR_{hk}, \text{inf}) \tag{3.14}$$

where h is the notation for the clock hour, k is the notation for k^{th} measurement for any hour h.

As per definition of infinite norm, such an operation gives the maximum non-negative value from a vector. PLR_{inf} is the infinite norm of all the measurements during each clock hour h, i.e. PLR_{h1}, PLR_{h2}, PLR_{h3}, ….. PLR_{hk}, and so on. This approach helps identify the maximum peak load reduction in any given hour. Again, if the maximum value of peak load reduction during any particular hour is to be picked, this approach can be useful. Such a value of PLR can show the best performance of a microgrid during different hours. This can be used to plan the peak load shaving requirement. The electric utility serving from the customer can then engage its own peak serving generation as per the maximum value obtained through this metric.

The peak load reduction values for the FortZED RDSI test run on September 1, 2011 are calculated for each of the test run clock hours through the methods given by (3.13) and (3.14).

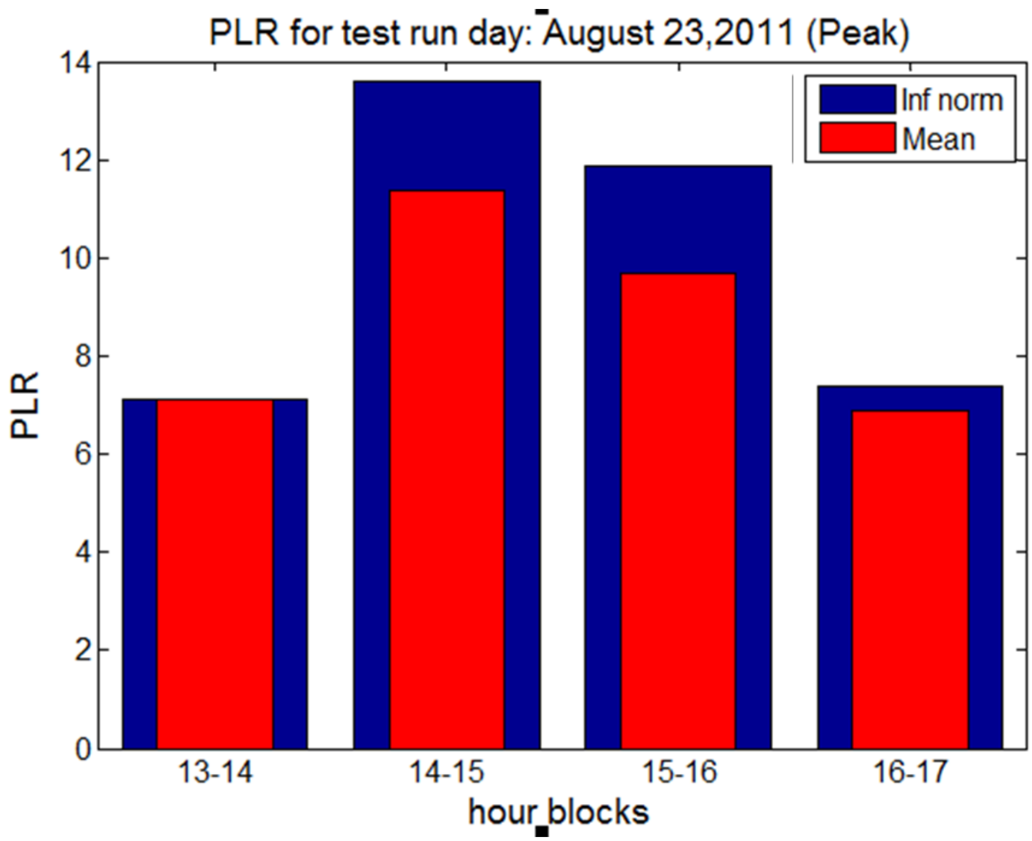


Figure 3.8 PLR through Approach-I and Approach-II for August 23, 2011

It may be observed here that maximum peak load reduction of about 13.5% occurs in clock hour block 14-15. The information from [3.10] suggests that the coincident peak hour as per the utility occurs during the block of clock hour 16-17. The peak load reduced during the peak hour is only about 7%. There is an opportunity of exploring the information presented through this metric to get a conservative value of peak load reduced by microgrid during coincident peak hour. Now, the utility can engage peak shaving assets accordingly. Although, in a shorter term, the planning may seem to have a negative impact through underutilization of peaking units used by utilities during coincident peak hours, it may be advantageous for both the microgrid and utilities in longer terms. The utility can defer the investment on such peaking units and as the load demand profile grows over time due to increase in customers, the underutilization can be negated slowly to reach full utilization of peaking units. PLR for other test run days using above two approaches are given in Table 3.3

Table 3.4 PLR (%) for various hour blocks using two approaches

Day	Hour from	Hour to	PLR Approach-I	PLR Approach-II
15-Aug	11	12	8.68	9.71
	12	13	8.61	10.12
	13	14	6.85	6.88
17-Aug	11	12	5.26	8.51
	12	13	8.81	10.07
	13	14	8.55	10.40
	14	15	6.93	7.13
	15	16	6.41	7.07
18-Aug	10	11	3.70	3.99
	11	12	8.12	9.04
	12	13	8.25	8.62
22-Aug	11	13	5.50	5.80
	13	14	5.18	5.18
	14	15	8.26	9.41
	15	16	8.15	9.70
	16	17	5.99	7.54
23-Aug	13	14	7.13	7.13
	14	15	11.36	13.58

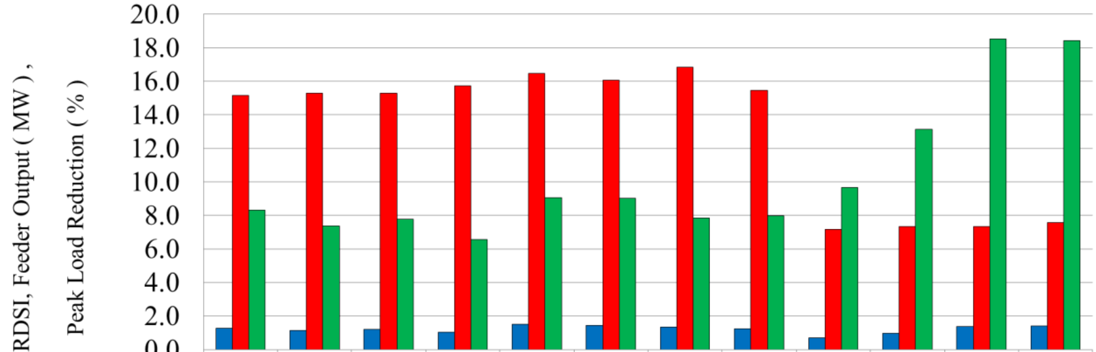
Day	Hour from	Hour to	PLR Approach-I	PLR Approach-II
23-Aug	15	16	9.68	11.86
	16	17	6.90	7.37
24-Aug	14	15	11.50	13.41
	15	16	11.18	13.64
	16	17	7.58	10.46
25-Aug	14	15	8.20	10.77
	15	16	9.27	10.12
	16	17	7.08	10.19
26-Aug	14	15	6.88	11.64
	15	16	9.96	11.54
	16	17	7.42	8.31
29-Aug	8	10	6.39	6.39
	10	11	8.87	9.42
	11	12	9.23	16.08
	12	13	14.68	15.95
	13	14	11.54	16.07
	14	15	9.21	11.47
	15	16	8.20	10.68
	16	17	5.31	8.56
30-Aug	10	11	10.06	11.01
	11	12	11.48	17.10
	12	13	16.36	18.98
	13	14	11.12	11.84

Day	Hour from	Hour to	PLR Approach-I	PLR Approach-II
31-Aug	9	10	11.51	15.76
	10	11	20.70	23.79
	11	12	20.45	21.56
1-Sep	10	11	9.99	13.66
	11	12	16.96	21.08
	12	13	19.73	23.33
	13	14	23.11	23.97
	14	15	22.88	24.55
	15	16	20.46	22.50

Approach-III: Mean over full day

$$PLR_{mean2} = \text{mean}(\ PLR(t)) \tag{3.15}$$

Using this approach the mean load reduction is calculated for each day and plotted as shown in Figure 3.9. This approach gives the peak load reduction averaged over all the run hours during a day. This directly correlates the amount of energy consumption reduction which can be a good estimate of net energy balance of system due to microgrid.



	Aug15	Aug17	Aug18	Aug22	Aug23	Aug24	Aug25	Aug26	Aug29	Aug30	Aug31	Sep01
RDSI Output	1.3	1.1	1.2	1.0	1.5	1.4	1.3	1.2	0.7	1.0	1.4	1.4
Total Feeder Load	15.2	15.3	15.3	15.7	16.5	16.1	16.8	15.5	7.2	7.3	7.3	7.6
Peak Load Reduction	8.3	7.4	7.8	6.6	9.0	9.0	7.8	8.0	9.7	13.1	18.5	18.4

Figure 3.9 PLR calculations using Approach-III.

Approach-IV: Infinite norm over full day

$$PLR(t)_{inf2} = norm(PLR(t), inf) \tag{3.16}$$

Approach-IV gives the maximum point of load reduction on each day. These vectors of metrics obtained through these two approaches can give valuable time based information by localizing it in the hour blocks. An advantage of such an operation is that only selective periods of time can be focused on, thereby making it easier to comprehend more from the formulation of the metric.

Such a metric could be helpful to an end-user like a distribution system operator who has to make decisions by scanning through and processing a large amount of data generated by the system. Although the information may not be of a fine resolution to make optimal decisions, it may help in deciding the course of an action on a short time notice, where detail for optimality may be compromised for more practical reasons.

3.5 System level control and deviations

The system level control deviations were a major criterion for performance assessment and smooth operation of the microgrid. The deviation is calculated here as difference of feeder load set point and the actual feeder power measurement.

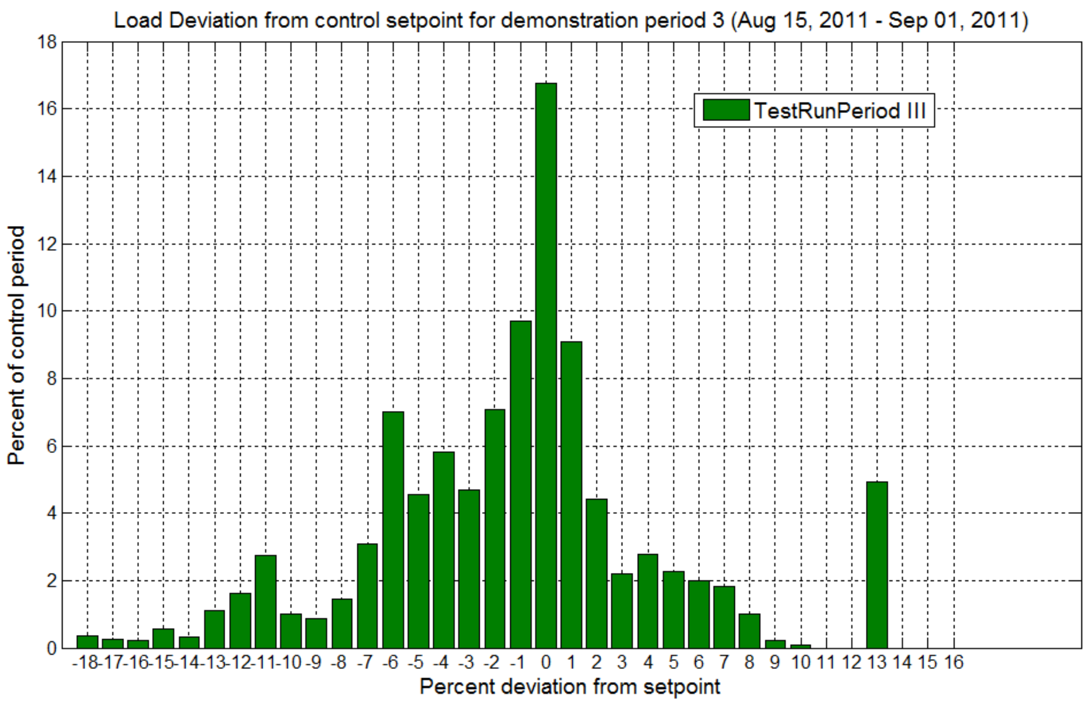


Figure 3.10 Load deviations from control set points as percent of control set points for the third demonstration period of FortZED RDSI

A positive deviation indicates a deficit in output of microgrid and a negative deviation indicates an excess. The bar at +13% bin can be attributed to the deviation during the initial ramp up of system when there would be a deficit. As seen from the plot in Figure 3.10 the system remains within +5% to -5% of deviations for almost 70% of control period. The sum of deviations due to initial ramp is approximately 5% of total control period. The system exceeds +5% of set point approximately 20% of the control period and is below -5% of set point only for approximately 5% of total control period. If the deviation for initial ramp up is ignored, the microgrid sufficiently serves the required loads adequately 95% of the total control period.

3.6 Interpreting the metrics for microgrids and application for planning

Traditionally, the electric power system (EPS) has not considered the microgrid as a supporting structure. Microgrid reserves can be used to mitigate generation-demand imbalance, especially during peak load hours and can also be used for ancillary services such as spinning, non-spinning reserves. Though this may seem far-fetched, with contemporary and future developments in controls and communication engineering and system integration methodologies, microgrids are expected to play a prominent role in the EPS.

A few of the existing metrics from NERC cannot be used for performance assessment of an asset or a group of assets, given the heterogeneity of assets. The metrics presented here have been calculated keeping in mind the interpretation of the definitions by NERC. The primary motive is to establish a benchmark for performance quantification and the approach followed to do the same so that the performance of assets in microgrids can be compared to those in the bulk power system, irrespective of the differing inherent nature of generation.

Metrics such as PRR and MPRR have been developed and can be used to plan reserves for microgrid operation based on previous runs. In conjunction with the analysis of past data, these metrics could provide a comprehensive insight into the reserves which can be used to enhance microgrid asset participation and avoid stranded costs of assets. PRR provides a view of reserve based on the capacity of the feeders and considers the electricity drawn from the EPS while MPRR focuses primarily on the operation of the microgrid alone.

REFERENCES:

[3.1] IEEE standard 493-2007 Gold Book, *IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems*, [Online]. Available: http://standards.ieee.org/findstds/standard/493-2007.html, Last Accessed 9/10/2012

[3.2] G. T. Heydt, R. Ayyanar, and R. Thallam, "IEEE Power Engineering Review," *IEEE Power Engineering Review*, vol. 21, no. 9, p. c2, Sep. 2001.

[3.3] G.T. Heydt, *Electric Power Quality*, vol. I. Stars in a circle publications, West Lafayette, IN, 1991, p.1.

[3.4] "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems," *IEEE Std 519-1992*, p. 0_1, 1993.

[3.5] NERC website, http://www.nerc.com/, Last Accessed 09/08/2012.

[3.6] NERC Generating Unit Statistical Brochure 2007, October 2008, [Online]. Available: http://www.nerc.com/page.php?cid=4%7C43%7C47

[3.7] 'RDSI Control Summary'. Email communications dated: 11/14/2011

[3.8] PRPA website, [Online], Available: http://www.prpa.org/services/loadinfo.htm, Last accessed: 10/29/2012

[3.9] M. Smith, 'Overview of US DOE's research and development activities in microgrid technologies'- presentation, SanDiego, September 2009

[3.10] P. Bauleo, 'PRPA peaks data 1986-2012', Email communications dated: 9/19/2012

Chapter-4

Visualization

This chapter describes the need, process, and examples of visualization for the analyzed data and performance metrics associated with the FortZED RDSI demonstration. The plots are provided for various metrics, and a graphical user interface (GUI) for visualizing the various metrics is developed in MATLAB is also presented.

4.1 Why visualize?

Microgrid operation generates a large amount of data. And since this data could valuable insight into the better operation of a microgrid, it could also provide information for both short and long term planning to work in tandem with bulk power system. Hence, the need for more comprehensive data analytics is deemed important. The information presented by any analysis on this data would be effective only if it is easy for the operator to understand. Making a decision while considering multiple variables becomes difficult and the complexity increases even more when decisions are to be made on a short time period. Thus, the information must be presented to the user (the operator in this case) as clearly as possible. Also, the information presented should also give the user a high level overview of the large scale system with the grid.

For the secure and optimal operation of power system, Federal Energy Regulatory Commission (FERC) has recommended the enhancement of situational awareness as one of the four priorities in its Smart Grid Policy Statement [4.1]. Although most work in the area of visualization in power system has been performed at the transmission level and large scale network monitoring, the salient points of such a requirement can be carried over for application to microgrid operation and planning.

Situational awareness can be described as “the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future.” [4.3]. Visualization must be developed for providing information that just producing data in a pictorial form. Some of the principles of display design which includes features such as legible displays, avoiding absolute judgment, using discernible elements, redundancy gain, minimizing information access cost, multiple resources and consistency [4.4].

Visualization provides one such way to present information in a meaningful and comprehensible form. A quicker assessment of the system state can be obtained by proper visualization of data or information using graphs as compared to data in numbers. A few of the characteristics of a good visualization would consist of easy to comprehend of information with the least cognitive effort by the user, dynamic response to the user’s requests to display the underlying characteristics of data, and the flexibility of control transfer to user as compared to applications [4.1].

4.2 Visualization for metrics : The FortZED RDSI microgrid case

The FortZED RDSI microgrid had 35 assets and the demonstration runs for the third phase (August 15-September1, 2011) consisted of about 50 hours of demonstration. As mentioned in Chapter 2 of this thesis, the data for each asset has a resolution of one second. The amount of data generated by the assets was of the order of 6.3 million data points only for power output values. Similar was the volume of command data set. For a capacity of around 2 MW, 35 assets consisted of the microgrid while for a similar large conventional generator, only 3 or 4 would be sufficient. Although, the change in size and number of assets does not necessarily increase the amount of data in exact proportion, there is still a considerable increase in data acquired by the SCADA. All the analyzed data and metrics are presented in form of visual charts, plots, and graphs. There are various ways to visualize metrics. Some of the plots for assets are given in Figures 4.1 to 4.6.

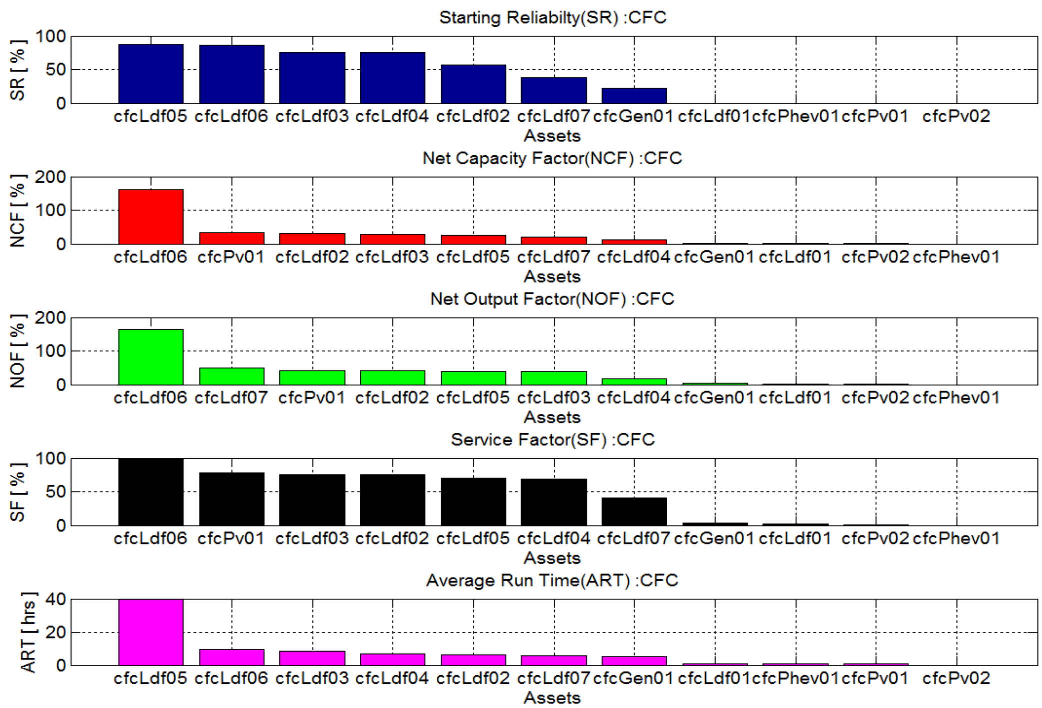


Figure 4.1 NERC metrics for City of Fort Collins

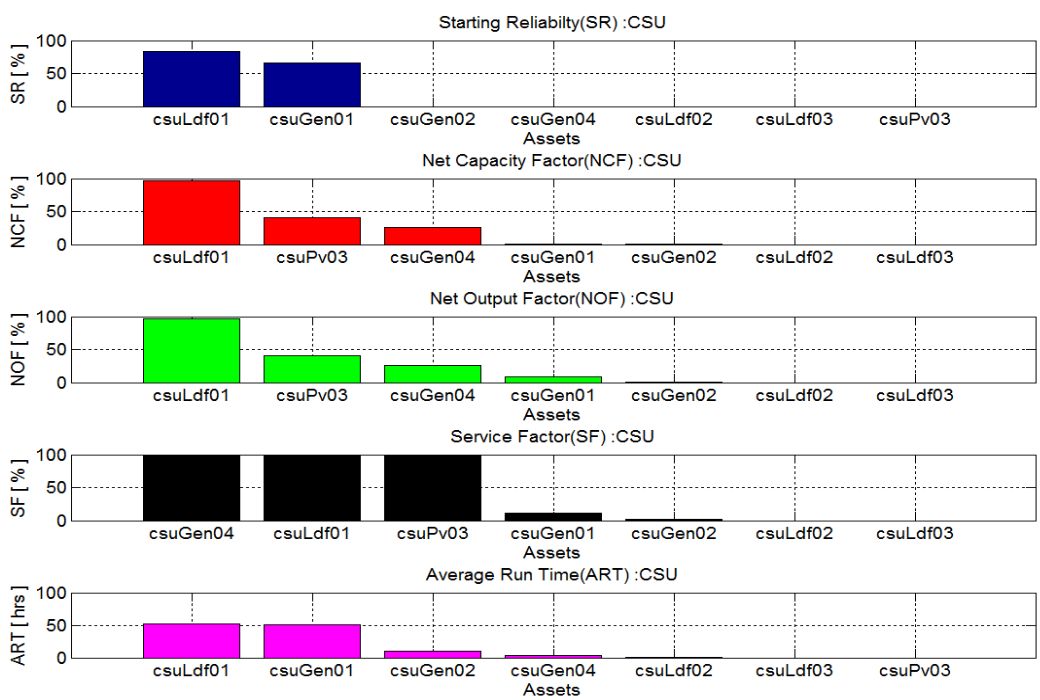


Figure 4.2 NERC metrics for Colorado State University – main campus

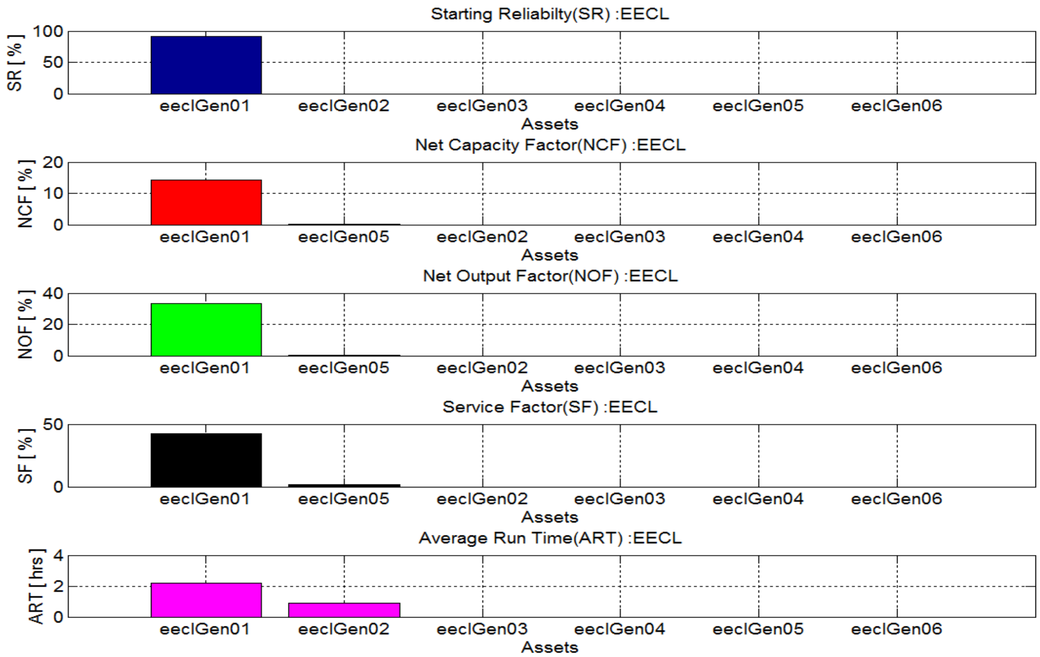


Figure 4.3 NERC metrics for Engines and Energy Conversion Lab

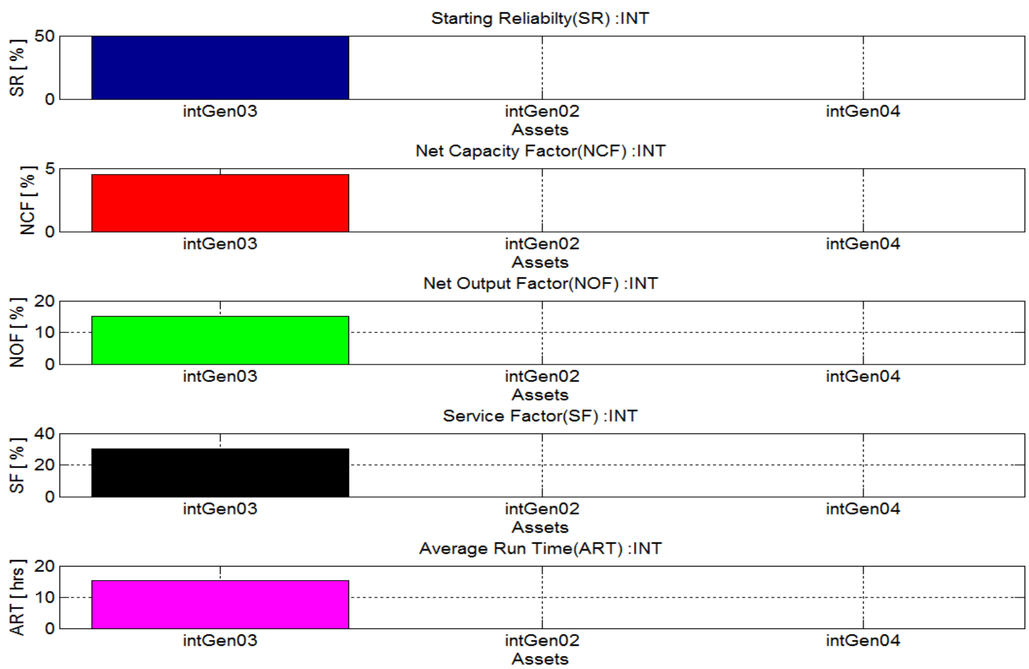


Figure 4.4 NERC metrics for InteGrid Lab

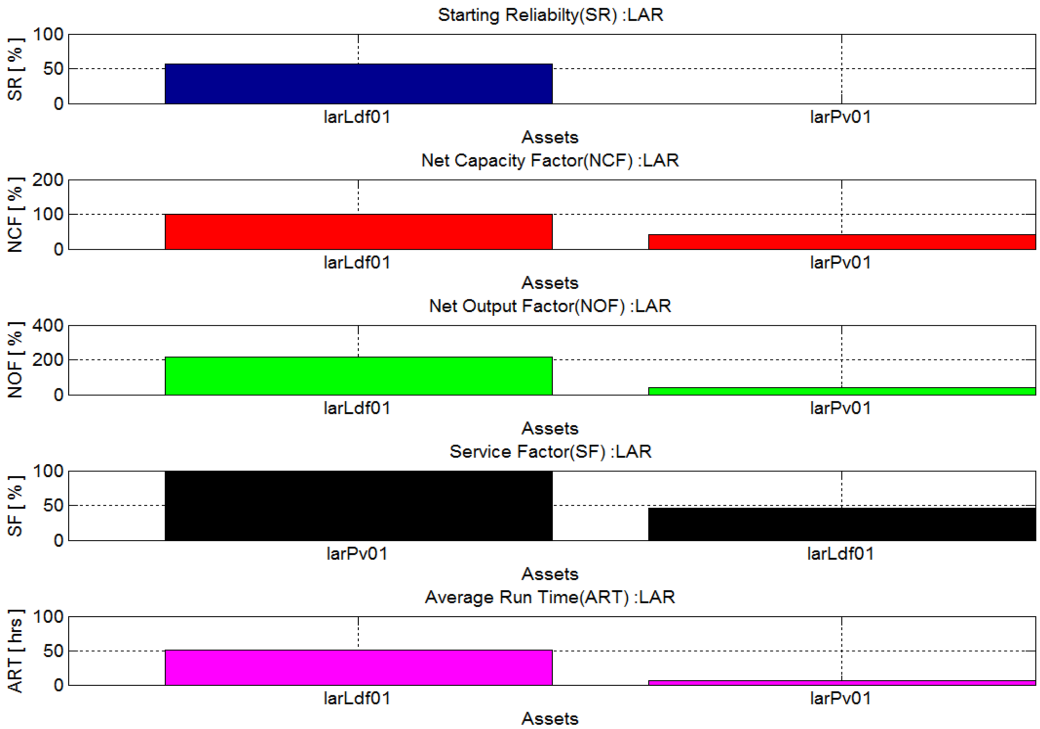


Figure 4.5 NERC metrics for Larimer County

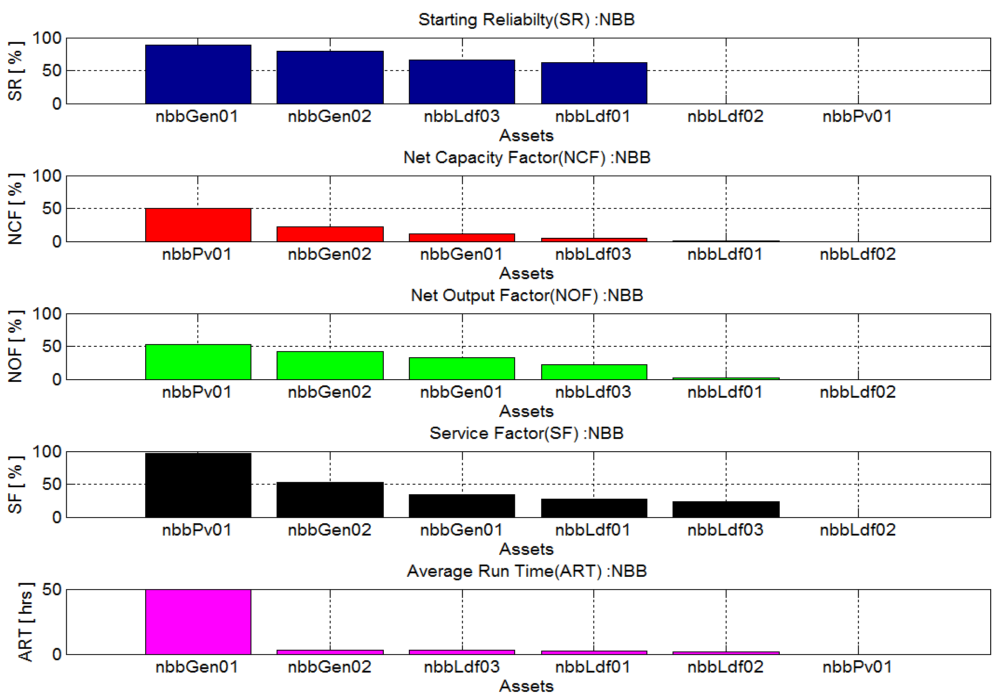


Figure 4.6 NERC metrics for New Belgium Brewing Co.

Each figure represents five NERC metrics namely SR, NCF, NOF, SF, and ART, for all the assets at a particular site. The values of each metric are arranged in descending order. All the plots in Figures 4.1 – 4.12 show the metrics calculated for third phase of test runs.

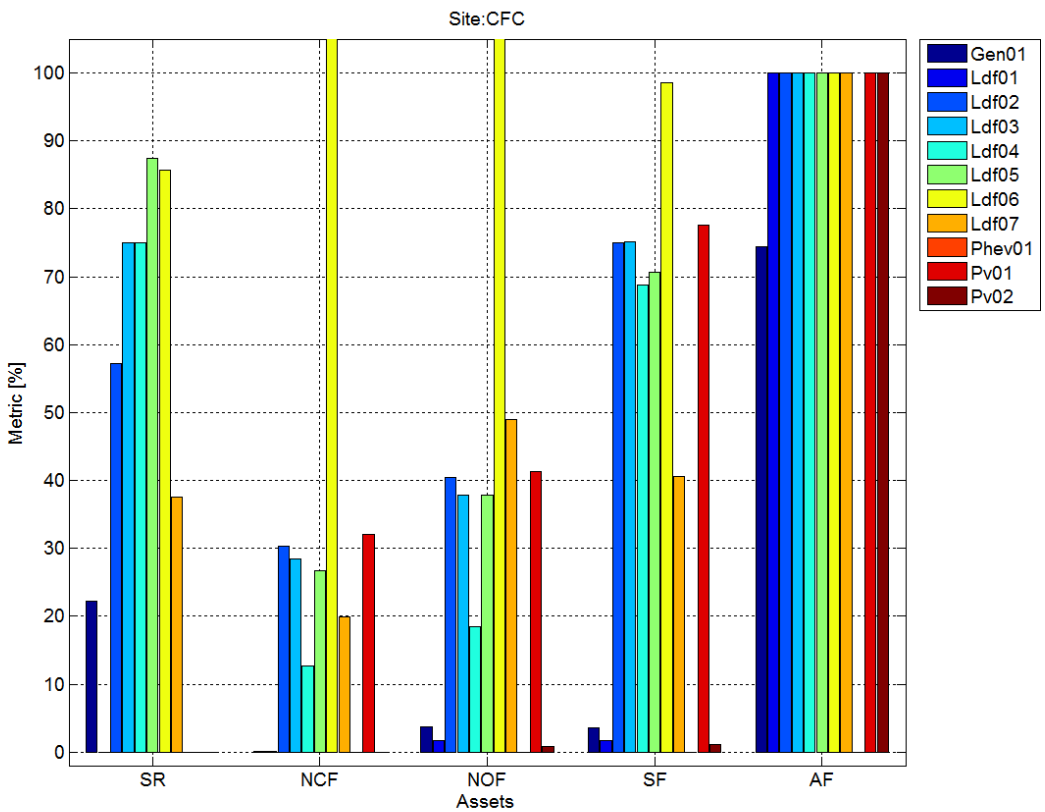


Figure 4.7 NERC metrics (grouped) for City of Fort Collins

Another simple modification to the visualization is the representation of metrics in grouped form. Each site is represented in a single plot with SR, NCF, NOF, SF, and ART values plotted for all the assets, one metric at a time. Figures 4.7 to 4.12 are shown for the same. The advantage of this form of representation is that all the metrics can be represented conveniently in a single plot, thus saving space. This is done keeping in mind representing more information per unit area of display usage. Use of different colors for different sites enhances clarity and better visual appreciation.

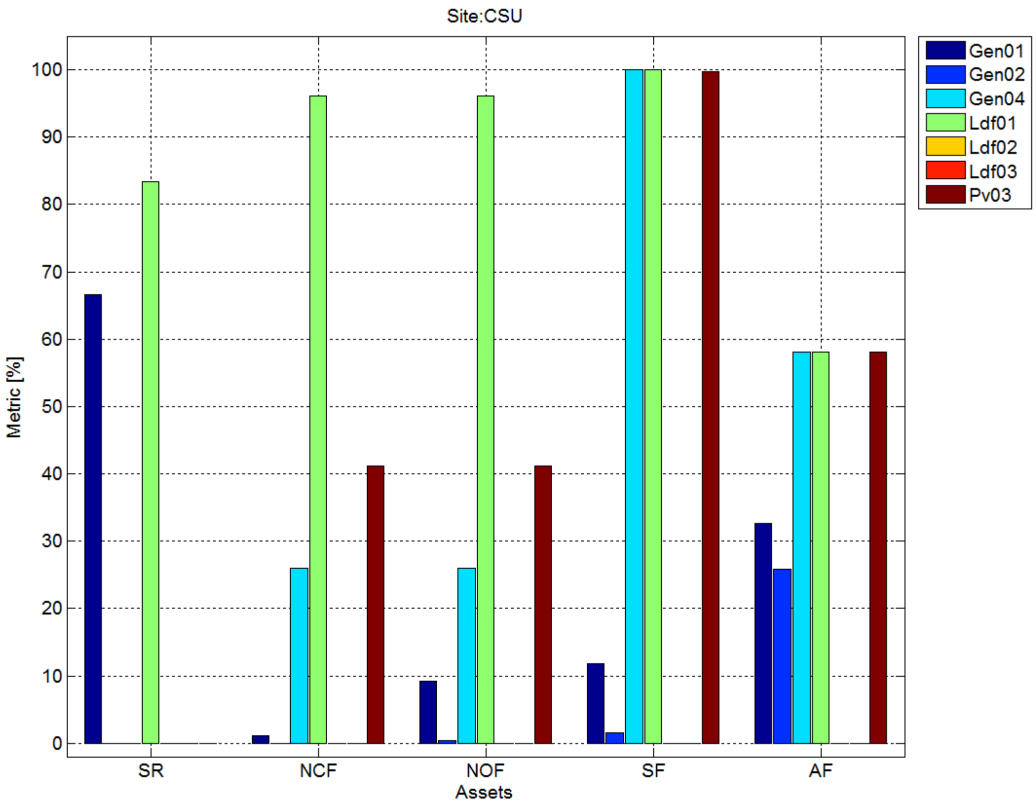


Figure 4.8 NERC metrics (grouped) for Colorado State University – main campus

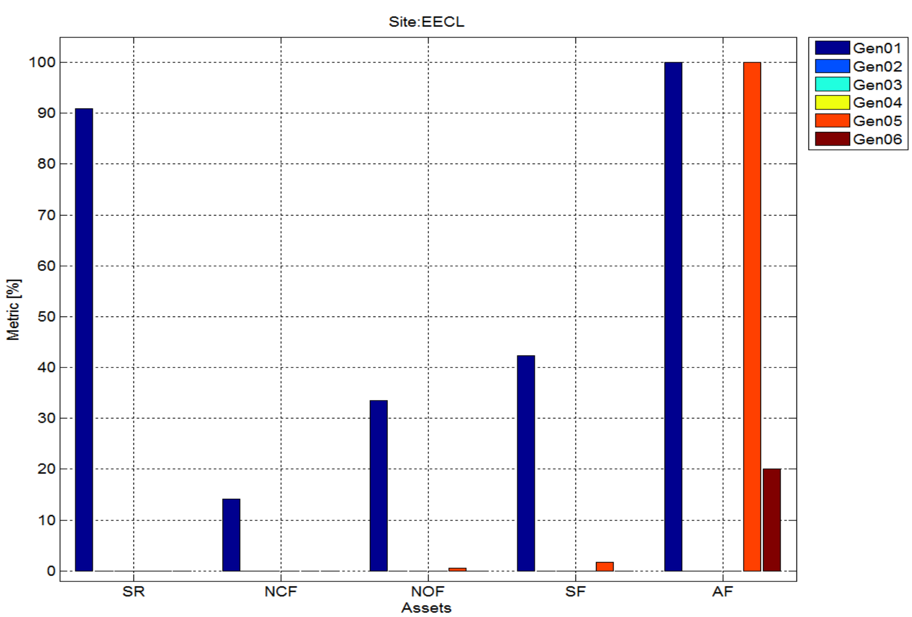


Figure 4.9 NERC metrics (grouped) for Engines and Energy Conversion Lab

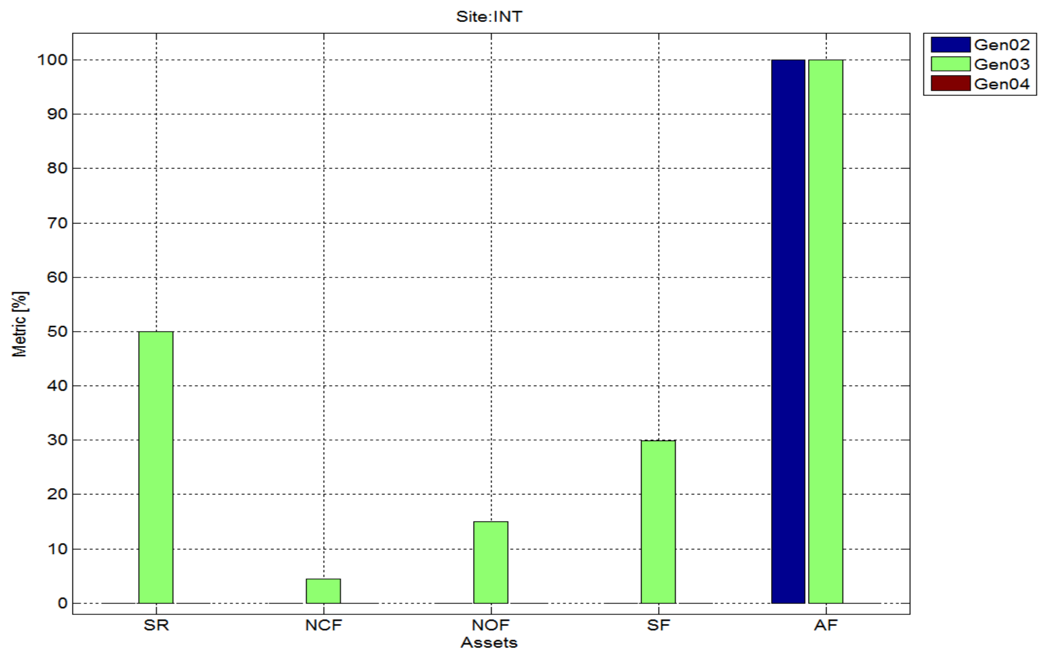


Figure 4.10 NERC metrics (grouped) for InteGrid Lab

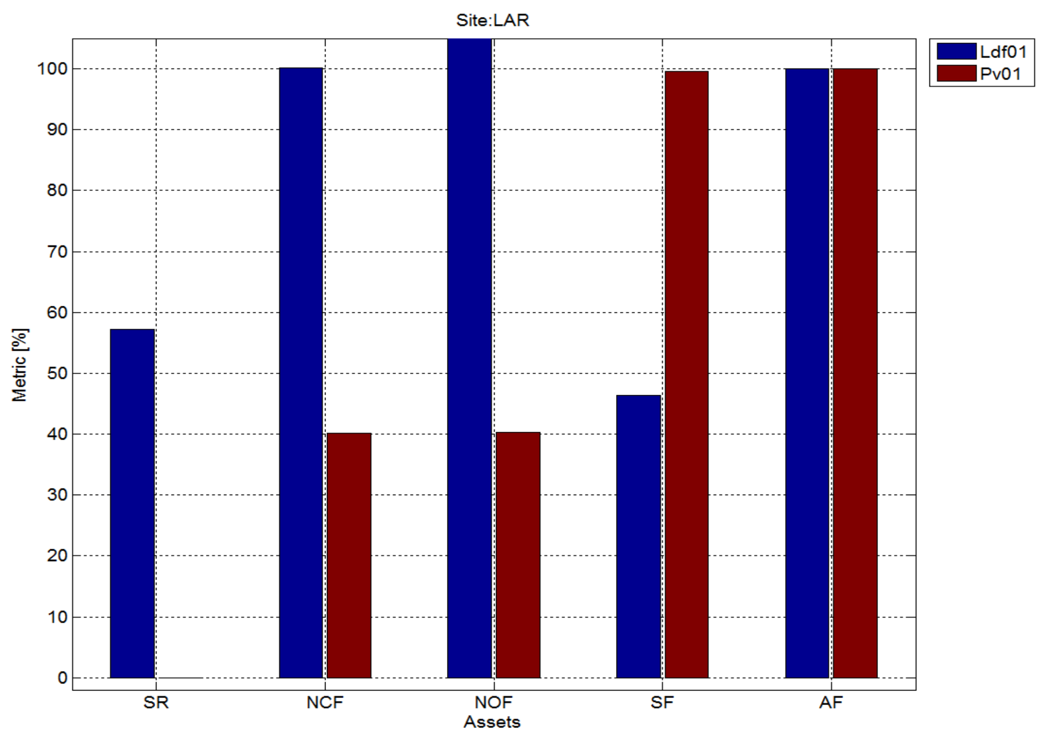


Figure 4.11 NERC metrics (grouped) for Larimer County

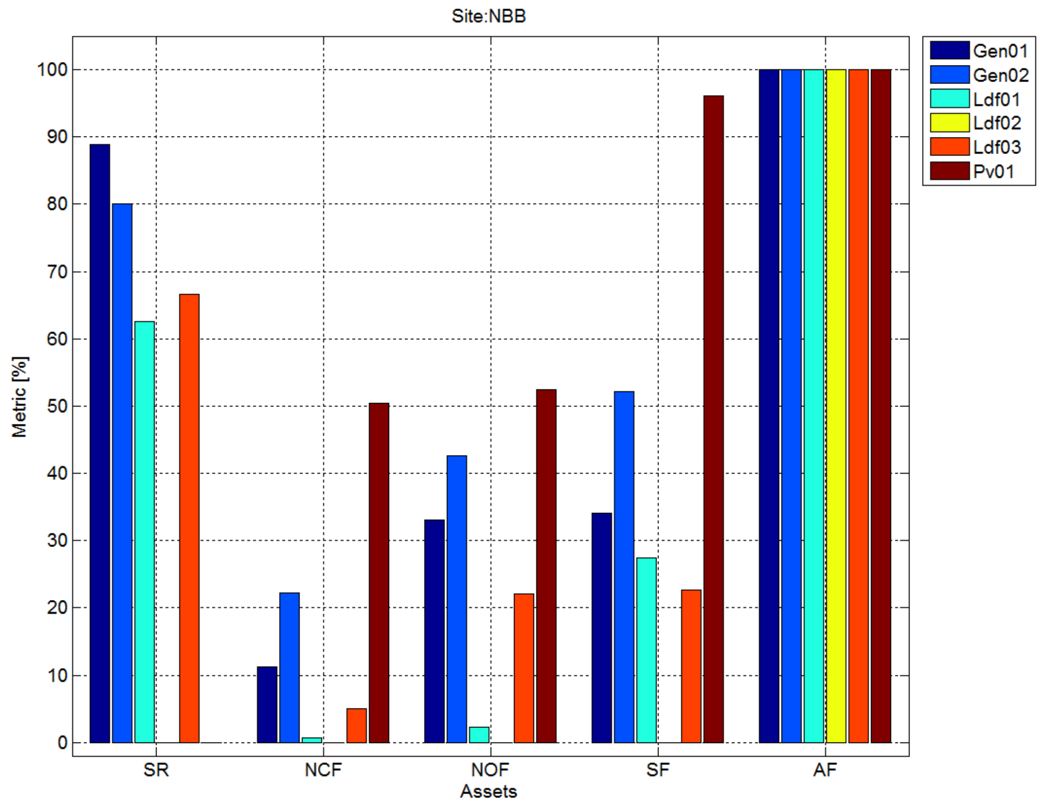


Figure 4.12 NERC metrics (grouped) for New Belgium brewing Co.

A legend is also provided for the easy identification of color corresponding to each asset. Such representation can present the metrics in a condensed form requiring minimal display space in applications for an operator's screen which may be running multiple displays simultaneously. It can be seen that such a display is sufficient for a basic display of metric information. Similarly, plots for other sites are also shown in Figures 4.7 to 4.12. The methods shown above are just some options available to display metrics. When displaying the plots for a post event analysis, it is not too difficult to analyze the information present in several graphs and charts. But when such information has to be displayed and used in near real time analysis for operation or asset allocation, it becomes cumbersome for a user to shuffle through graphs to obtain information from multiple inputs. Therefore, a platform to display maximum possible pertinent information as required by a user at a time of decision making can help in this regard. A user interface in such a situation other than command line interface (CLI) can be very effective. A GUI is one such tool to provide enhanced man to machine interaction. The GUI developed in MATLAB for displaying the data and metrics is presented below.

4.3 Visualization assemblage : Graphical User Interface for metrics

A GUI was built in MATLAB® for visualization assemblage of all metrics and data analysis results. The GUI is a one stop tool for accessing all of the information from data and displaying it visually for enhanced situational awareness. Some of the features and functionalities of the GUI are given below:

(i) **The GUI has the option for multiple plots to aid comparison.** Any two different metrics for the same asset or site, or the same metric for two different assets or sites, or the feeder level data for two days with feeder level metrics for corresponding days can be compared by simultaneous display. This is valuable for relative benchmarking. Figure 4.13 shows an example plot for PRR on two days: Aug23 and Aug25 at resolution = 1s

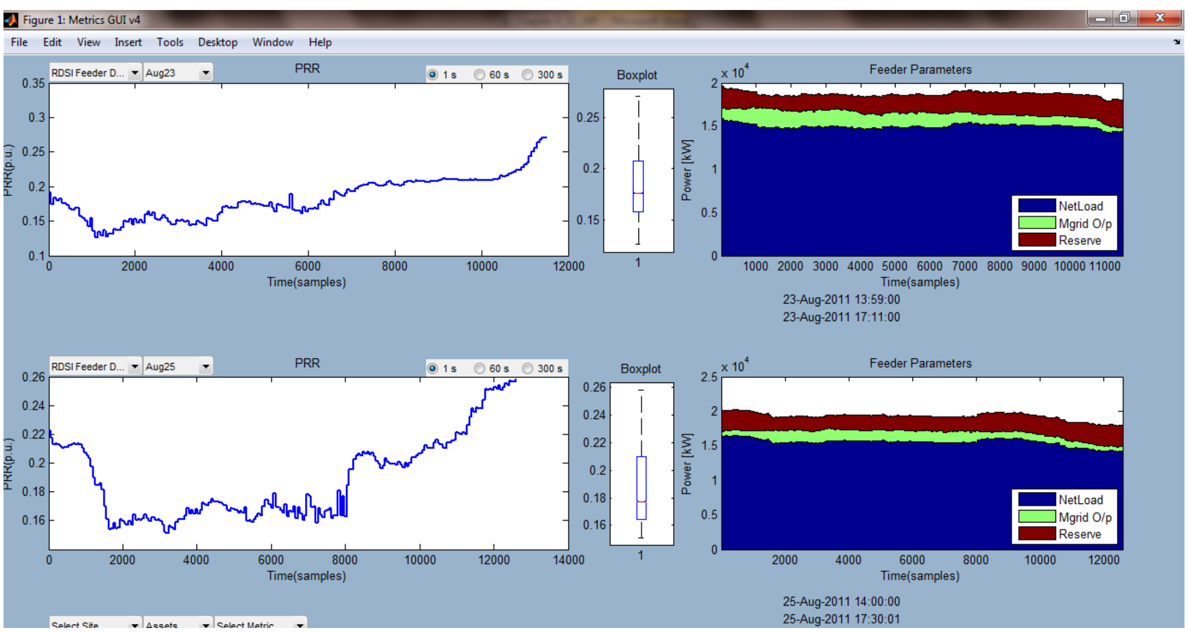


Figure 4.13 Multiple plots for comparing metrics

(ii) Boxplots for feeder metrics and area plots for feeder level power outputs. These are plotted on two different plot areas when a user selects a particular day from the drop down menu. MPRR and PRR are calculated and plotted for this data. Figure 4.14 shows the boxplot for the same example as for Figure 4.13. The boxplots give an idea about spread of the metric and the three quartiles and outliers can be easily seen which are not so easy to identify by looking at the time series plots. The area plots for feeder level measurements of net feeder load, microgrid output and microgrid reserve are plotted. Looking at the area plot, the user can easily get the idea of total feeder load and microgrid capacity by adding up blue and green for total feeder load and green and red for microgrid capacity.

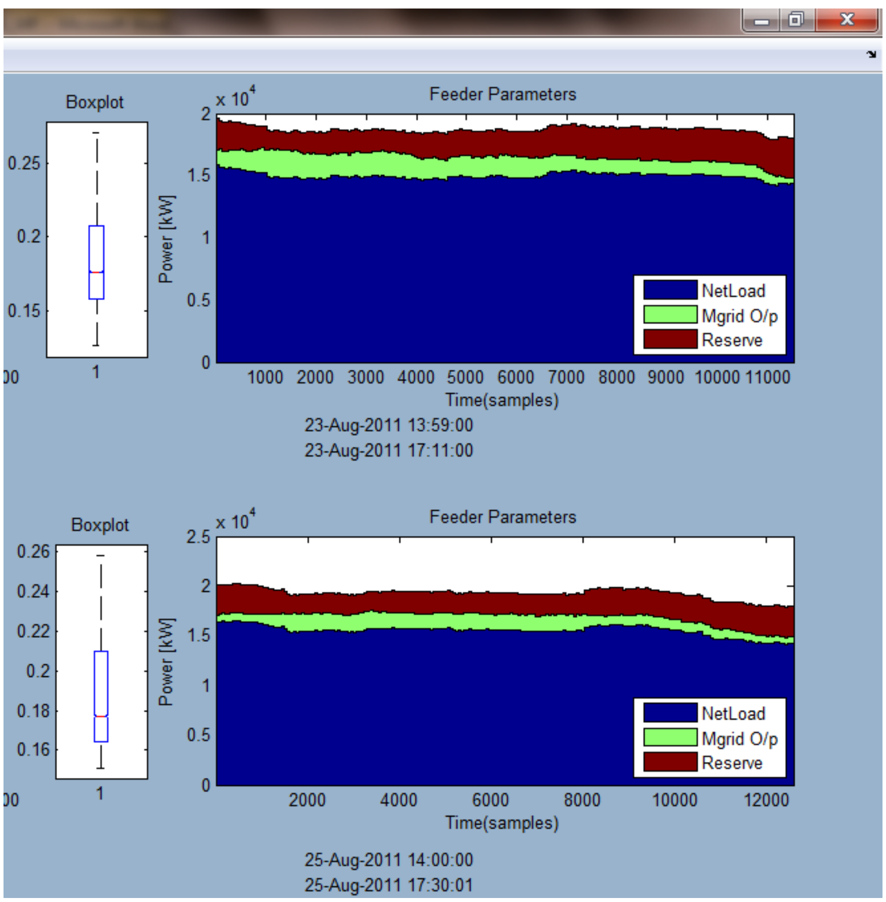


Figure 4.14 Boxplots and area plots for data visualization

(iii) The resolution of feeder level data can be selected by the user. Analysis can be performed at three resolutions: 1s, 60s and 300s. It is the discretion of the user to select the granularity required for analysis. Sometimes it may be desirable to make calculations which do not require a lot of accuracy. To save computational effort, the resolution of the data may be reduced. This reduces the number of data points to be handled for computation. When the data at the scale of millions of data points is to be processed, a small loss in granularity by reducing resolution may benefit greatly in computation. Default resolution is 1s. Start and end time information for data is also displayed. Figure 4.15 shows the option to choose the resolution of data set to be used for data display and metric calculation. The options can be seen on right top corner of the first two plot areas as 1s (default), 60s and 300s. The user can chose the granularity based on the task to be accomplished.

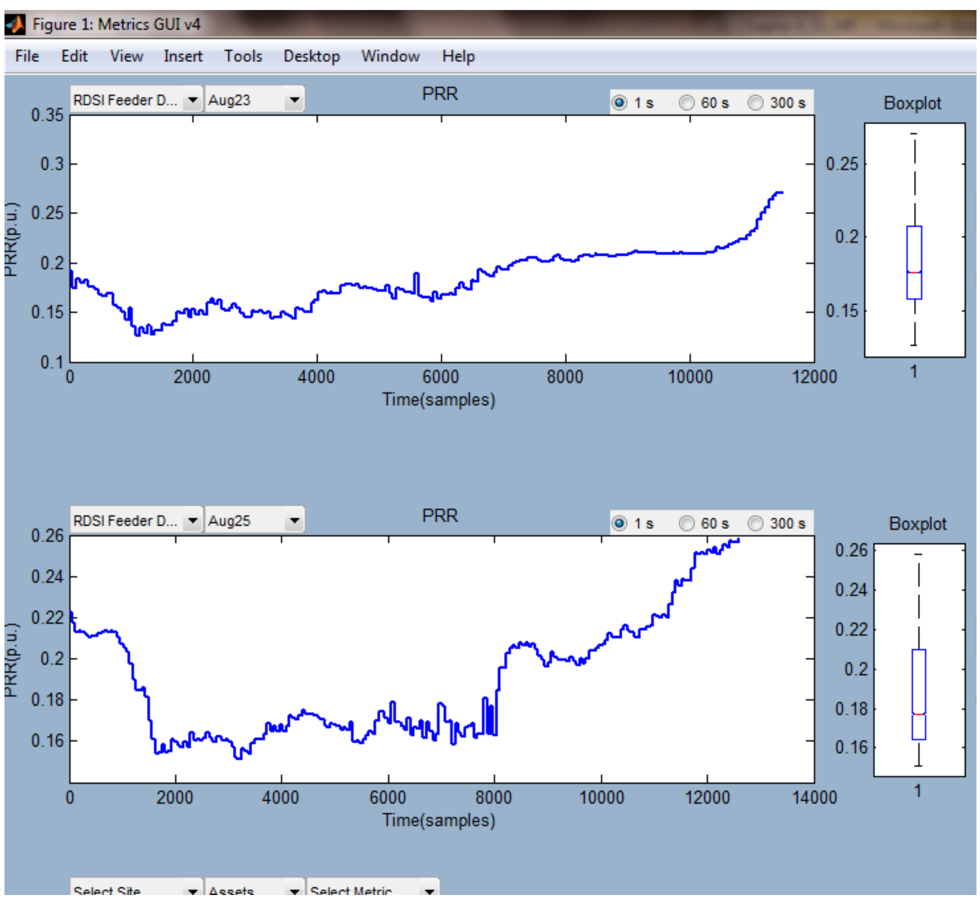


Figure 4.15 Resolution selection feature for feeder level data

(iv) The asset data to be displayed can be selected by the user. The metrics can be calculated and displayed only for the selected time period starting from August 15, 2011 00:00:00 hrs to September 02, 2011 00:00:00 hrs. The resolution of this data is one second and slicing of data can be done in a step size of 15 minutes. Most planning and revisions are done based on data in time block intervals of 15 minutes or multiples of it, hence the step size in slider for slicing data. Only the test run time lying in the selected time period is considered for the metric calculation. Figure 4.16 shows the feature of slicing the data to desired time periods and then analysis can be performed on it. At times, it may be desirable to observe the performance of the asset or microgrid system for a shorter period of time. The sliced data set can be used for this purpose.

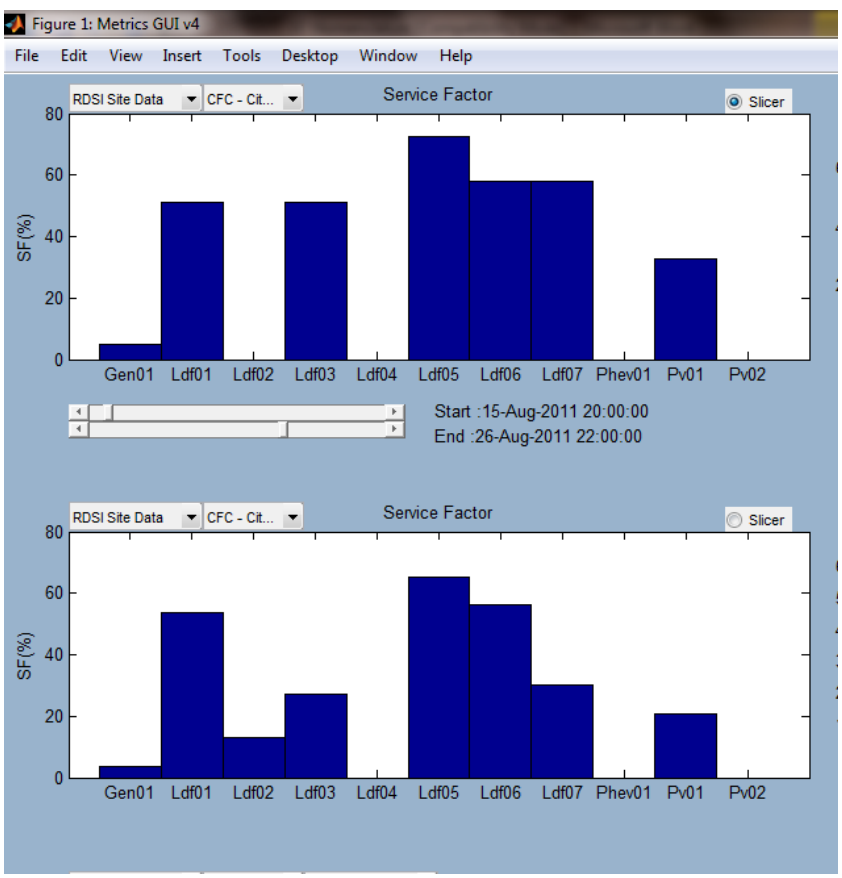


Figure 4.16 Slicing feature in GUI for site, asset level data

(v) Tabular representation and boxplots for NERC metrics. Bar graphs for the NERC metrics viz., SR, NCF, NOF, SF, AF, and ART for asset level and the WSF and WAF for the site level are plotted. Numerical values are also available for display for a more detailed comparison which is not easily observable from the bar graphs. Figure 4.17 shows the metrics displayed for site level data are plotted as boxplots too with each site or asset having one metric value and spread of whole site or all sites can be obtained. Tabular representation gives an accurate representation when details are needed and information is not discernible visually. This reinforces the principle of redundancy as mentioned earlier in this chapter.

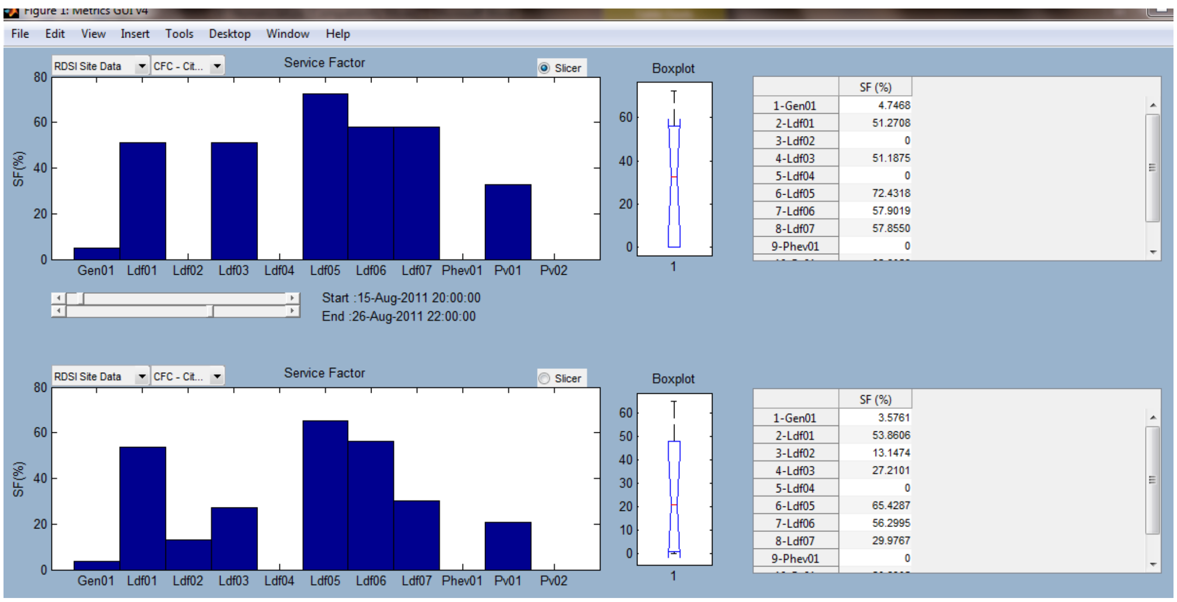


Figure 4.17 Tabular displays of metrics for more accurate observation

(vi) Metric description as per NERC. Whenever a user selects a particular metric to be calculated, a description (mathematical formula) of the metric appears just above the location of buttons for metrics in the GUI. Although a trained operator would be well versed with the description, it provides clarity to a new user and is also available for reference if needed. This may prove useful in times of emergency decision making thereby reducing risk of human errors due to misinterpretation of metric.

Figure 4.18 shows the snapshot of metric definition which appears when the user presses the button for desired metric.

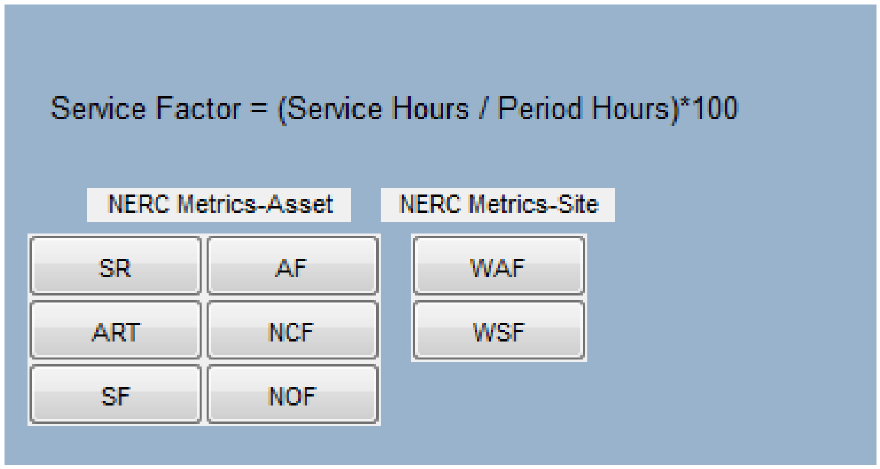


Figure 4.18 Metric definitions and description in the GUI

(vii) Time varying observation of metrics. Another feature available in the GUI is the calculation and visualization of a time based metric. This feature is available only for individual assets, so the grouped NERC metrics WSF and WAF cannot be seen in this plot. The site, asset and metric can be selected from the drop down menus provided above the plots. Apart from the time varying metric plot, a scaled image color plot is also displayed for the same metric. This provides a coarser look into the variation of the metric over time. The values are represented by colors corresponding to the chosen color-map, 'Red' being highest (100%, or 100 hours) and 'Blue' being the lowest value (0%, or 0 hours). The other plot in the calculation of the time varying metric is the power output. The calculation of the power output is done with a window expanding in time by 15 minutes on each step. So, the first sample is at 0s, second at 15minutes but considers data of past 15 minutes, third of past 30 minutes, but considers the data of the past 30 minutes. The starting point of window is fixed at start of the test run and keeps on expanding by one block on every iteration. Each block is equal to 15 minutes. The reason for doing this was to obtain sufficient amount of data to process and calculate the metric. Since most of these metrics based on large amounts of data, historically, it is left to the user to program and fix the length of window as desired. For example, for a day worth of data for calculations, past 96 blocks of data may be used for calculations and iterated till end of the period. A fixed window size of 96 blocks can thus be used for calculations. This way the information is obtained from a consistent length of data and can be used in the decision making process for planning and operation. Since, short term planning is usually done on a day-ahead basis and can use data from the past 24 hours or even a longer time period, the option of the window size selection is instrumental to obtain useful information for decision making [4.2].

Figure 4.13 shows the snapshot of the GUI with some examples plotted for metrics. The first plot in top-left shows variation of the metric PRR for test run day of August 17, 2011. The calculations have been done for feeder data sampled at 1s. An option to select 60s, or 300s is also available as seen in the radio buttons present on top right end of each plot are for metrics. The right adjacent graph is a boxplot for the spread of PRR which gives the quartile values for the data set and also the outliers. The area plot in right top corner is displaying the feeder level data for microgrid power output, net feeder load and microgrid reserve. All values are displayed in kilowatts for data sampled at 1s, as selected from the radio buttons. The bar graph (second from top left) is displaying the NERC metric WAF for all the FortZED RDSI sites. The slicer is active and the sliders below show the starting and end times of the sliced data, and the calculations are made on the same. The adjacent right boxplot is again the spread of the set of metric values for each site. A tabular representation of the metrics is also provided for more accurate comprehension of values, if required.

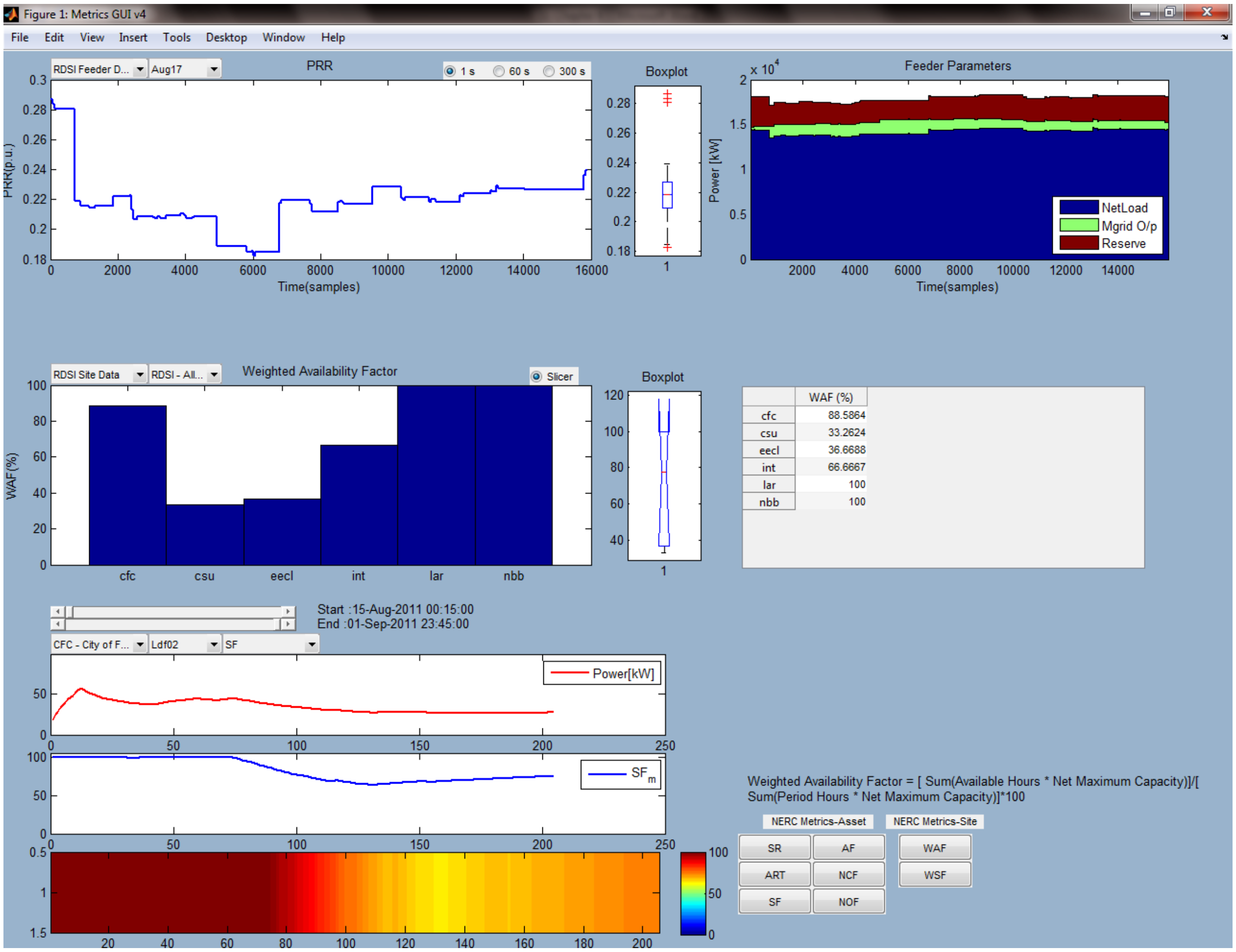


Figure 4.19 Snapshot of visualization GUI displaying metrics for asset and feeder data

The last three plots on the left side are for the time varying metric representations. The site, asset and metric to be plotted in time can be selected from the drop down menus on the top of the plot area. The power output value of the selected asset is displayed. This calculation is also done on a expading window pivotted at start of test run period. The length of each block is 15 minutes and the window length keeps on increasing by one block on each iteration. The next plot shown in the snapshot is for the NERC metric SF for asset *cfcLdf02*. Another plot for the same mmetric is displayed as a color variation image plot with colorbar legend shown alongside the plot. Such visual representation is very appealing to a user when scanning peformance of an asset on a coarse basis. But, the color change here is quite subtle for smaller changes in value given the linear colormap is used for the plots. A non-linear scaling can be used to discern subtle changes when required. The MATLAB® script for the visualization and GUI can be found in supplementary documents provided with the thesis.

REFERENCES:

[4.1] J. Zhu, E. Zhuang, C. Ivanov, and Z. Yao, "A Data-Driven Approach to Interactive Visualization of Power Systems," IEEE Transactions on Power Systems, vol. 26, no. 4, pp. 2539 –2546, Nov. 2011.

[4.2] T. Ohashi and T. Ono, "Visualization and interactive simulation for power system operation and education," in Advances in Power System Control, Operation and Management, 1997. APSCOM-97. Fourth International Conference on (Conf. Publ. No. 450), 1997, vol. 2, pp. 802 –807 vol.2.

[4.3] J.H. Obradovich, Alison Silverstein, 'North American Synchrophasor Initiative (NASPI) Phasor Tools Visualization Workshop- Final Report', February 28, 2012, [Online], Available: https://www.naspi.org/ pp. 3-4.

[4.4] Christopher D. Wickens, John D.Lee, YiliLiu, and Sallie E.Becker (2004), " An Introduction to Human Factors Engineering", Second ed.,Upper Saddle River, NJ:Pearson PrenticeHall,185–93.

Chapter-5

Conclusions and future work

Some methods for reliability quantification and visualization were presented for electric microgrids with an example of an actual microgrid demonstration run, i.e. FortZED RDSI project.

5.1 Conclusions

Data reduction and handling were the initial steps before performing data analysis. This was done using MATLAB® and Simulink®. Logical indexing of vectors proved useful when handling large amounts of data. Data was checked for consistency at each step of the reduction process. Since the data was for a short test run period, efforts were made to keep original data synthetically unaltered as much as possible. Any excursions, outliers, repetitive time stamps, missing fields for power or command were excluded from the data set. Assets with missing fields were not used for calculation of metrics to avoid erroneous results. The command data set was modified for easier change interpretation and better visual appreciation when plotted against time. Various metrics for performance assessment were calculated using existing NERC criterion which is followed by the electric utilities in North America. The methodology for metric calculations was explored in detail and process algorithms were explained using flowcharts and diagrams. The input variables used in metric formulas, as per existing NERC criterion, were interpreted in perspective of microgrids to closely follow the concept of quantifying each performance characteristic of power system asset. The data for the demonstration spanned only a few hours and only power and command information was available in time. Information from test run reports, such as test run set-point, response time considered by control system for dispatching assets, asset availability and asset ratings were also used for calculation of the metrics. Apart from the calculation of the metrics defined by existing criterion of NERC, **two new metrics were proposed to quantify microgrid performance with potential use in design, planning, and planning by the operator**.

The main aim of the FortZED RDSI demonstration was reduction of peak load by 20-30% of total feeder load. So, the calculations were done for percent peak load reduced on each day of the test run. The DOE requirement states a minimum of 15% reduction while FortZED aimed at 20-30% reduction. The average peak load reduction varied on the 12 days of the third phase of demonstrations, and ranged from 6-18% of total feeder load on the particular day. **Various methods for calculation of peak load reduction were explored and a few new approaches on a congruent time scale were presented to suit the techno-commercial aspects of future microgrids**.

Visualization of data and information was another focus of this work. Calculated metrics were presented in simple visual forms using bar charts, line plots, and box plots for assets grouped together based on different criteria such as site location, type, and metric value. For easier exploration of the different metrics for multiple assets, an assemblage of visualization was presented in the form of a GUI. This GUI is aimed at providing better visualization, increased user interaction and flexibility of information display to the end user. **This GUI is a deployable tool to aid the operator for enhanced situational awareness and informed decision making.** The evolution of the metrics over time provides a clear picture of performance of an asset and this feature has been added to the GUI. But, it still has open questions on the levels of data granularity, data amount and the length of the time window under consideration for the desired information. These would vary on a case by case basis depending upon the role and the scale of commercial operation of a microgrid.

A few observations were made during the data processing and handling phase of the process which can be accounted to the nature of data acquisition and instrumentation, like the dead banded data, issues with storage of data for individual assets, and difference in reconciliation of feeder data to sum of asset outputs. The data capture and storage employed a technique to dead band data, i.e. no new data point is recorded and stored unless it changes beyond a preset dead band. This dead band for power output values of assets was 1kW. This may be insignificant for a system of the order of megawatt capacity but since the number of assets in a microgrid is large, the individual asset capacity is small and varied from 1.2 kW for a load shedding asset to 522 kW for a conventional generator for FortZED RDSI. Applying the same dead band for each asset may result in low resolution value of acquired data and result in larger inaccuracies when aggregated over the whole system. An approach that can be adopted is to reduce the dead band of data acquisition and storage for higher resolution. Second issue was that this dead band allowed less storage capacity and non-continual time data capture. During a time based analysis this data had to be synthetically treated using zero-order hold principle and sampled. An approach to mitigate this problem would be to capture the data continuously in time with a higher time resolution. The time resolution on original data was 1s. A higher resolution of data capture, say in the order of a 10 or 100ms can be crucial for a better response analysis of fast acting systems like conventional generators. There were a few issues with successfully synchronizing some of the generators to the main grid. A finer resolution data may help in a root cause analysis of the problems. The third issue was the inability of reconciliation of microgrid output as per the feeder level data set with sum of asset outputs for the same test period. Few calculations for feeder level measurements were done on near real time basis using the asset power outputs which were then stored in the data acquisition system. When the outputs of assets as stored in data files were analyzed and summed up to get feeder level data, both dataset outputs did not match. Another issue was that the start time and the end time for command and power output for an asset did not match. Sometimes the command values were present for only a part of the data set, i.e. time stamp inconsistency of power and command values for same asset. The demand response asset controllability was also not as expected and some of these assets often shed more than they committed to. A better interfacing of control system and building automation system can be a key improvement for future operations.

5.2 Future work

The results from the work presented here can be applied to microgrid design, operation and planning based on performance of assets. But, the metrics alone would not suffice the decision making process and must be integrated into the asset scheduling and dispatch methodologies adopted by the operator and/or the control system. Reliability quantification can be explored more in detail and several other metrics may be formed which establish a stronger relationship between long term planning and operation. Deterministic reserve and contingency planning tools may be built which are more accurate and rigorous. Probabilistic modeling of individual assets and group of assets, based on various criteria, can be done which can be used to achieve increased power system reliability through microgrids.

Visualization can be taken to the next level by introducing more complex data and visualization of information more efficiently. The next step would be to go from post event to near real time analysis and visualization.

LIST OF ABBREVIATIONS

AF	Availability Factor
AMI	Advanced Metering Infrastructure
APEL	Advanced Power Engineering Lab
APEN	Air Pollution Emission Notice
ART	Average Run Time
CDPHE	Colorado Department of Public Health and Environment
ceil	MATLAB function for greatest positive integer
CERTS	US Centre for Energy Reliability Technology Solutions
CFC	City of Fort Collins
CFL	Compact Fluorescent Light
CHP	Combined Heat and Power
C_i	ith command change indices
CSU	Colorado State University
CSV	Comma Separated Value
DG	Distributed Generation
DR	Demand Response
EECL	Engines and Energy Conversion Lab
EMS	Energy Management System
EPA	Environmental Protection Agency
EPS	Electric Power System
ERO	Electric Reliability Organization

FCU	Fort Collins Utilities
FERC	Federal Energy Regulatory Commission
FortZED	Fort Collins Zero Energy District
GUI	Graphical User Interface
h	Clock hour ‘h’
HVAC	Heating Ventilation Air Conditioning
INT	InteGrid Lab
IT	Information Technology
k	Observation in an hour
LAR	Larimer County Courthouse
LED	Light Emitting Diode
MPRR	Microgrid Peak Reserve Ratio
NBB	New Belgium Brewing Company
NCF	Net Capacity Factor
NERC	North American Electricity Reliability Corporation
NOF	Net Output Factor
PCC	Point of Common Coupling
PHEV	Plug-in Hybrid Electric Vehicle
PLR	Peak Load Reduction
PMU	Phasor Measurement Unit
PRPA	Platte River Power Authority
PRR	Peak Reserve Ratio
RDSI	Renewable and Distributed Systems Integration

RMT	Response Monitoring Time
SCADA	Supervisory Control And Data Acquisition
SF	Service Factor
SR	Starting Reliability
t	Time dependence of a metric
T&D	Transmission and Distribution
V2G	Vehicle to Grid
WAF	Weighted Availability Factor
WSF	Weighted Service Factor