Secure and reliable deployment of large scale Demand Response in a futuristic smart grid

By

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Session 2015 – 17

Supervised by

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Masters of Science in

ENERGY SYSTEMS ENGINEERING

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A Thesis Submitted to the *U.S. – Pakistan Center for Advanced Studies in Energy* in partial fulfilment of the requirements for the degree of

MASTERS of SCIENCE in

ENERGY SYSTEMS ENGINEERING

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July 2019

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Dedicated to my

Parents (especially dear and patient Mother),

Siblings,

Friends and

Giants whose shoulders I stood on.

ACKNOWLEDGEMENTS

I am indebted to my advisor, Dr. Kashif Imran (HoD EPE Department), for providing invaluable guidance, time and support in completion of this thesis. In addition to, I am extending my gratitude to my GEC Members, including Dr. Adeel Javed (HoD TEE Department), Dr. Rabia Liaquat (ESE Department) and Dr. Abraiz Khattak (EPE Department), for their supervision and feedback as well.

Moreover, the genesis of this thesis was provided by Dr. Hassan Wajahat Qazi (Sr. Engr. EirGrid Ireland) – I appreciate his support and technical insights during his brief stay at NUST.

I also acknowledge the support of teaching and non-teaching faculty of U.S.-Pakistan Center for Advanced Studies in Energy for all the things that facilitated smooth work of my academics and research. Similarly, the support staff throughout NUST, in various capacities, has my heartiest thank-you.

To all those whom I am not mentioning here due to paucity of space; ***YOU*** will remain in my wishes and prayers.

ABSTRACT

Electricity grid of the future is envisioned as ‘smart’ and ‘green’ thanks to increasing renewable energy (RE) penetration and advancements in information technologies that allow control of energy flow with respect to associated data such as load profiling and real-time energy prices. Demand Response (DR) is a key component of a smart grid control strategy to ensure system stability and reliable energy delivery. DR is the process of controlling end-use customers (load) for the provision of power balance, while maintaining consumer comfort. It can be used to mitigate power imbalance following a contingency such as loss of largest generation/load. Significant research has been carried out previously to suggest DR based power balance provision i.e. contingency reserve provision, however the focus has been on active power balancing or on the distribution systems (Voltage level less than 132kV). There is, however, a dearth of literature concerning DR activity impacts on high voltage transmission system (230kV and above) and system reactive power. Therefore, this thesis has focused on investigating the transmission system impacts of DR with respect to both active and reactive power balancing. A sensitivity-based analysis has been carried out, investigating the impacts of DR based load composition, magnitude and location. The analysis has been carried out in the open source environment of MATPOWER tool and focused on dependent variables such as real and reactive power losses, bus voltages and angles. Based on the sensitivity analysis, DR load optimization in terms of magnitude, composition and location has been carried out so as to maximize system reliability and efficiency.

Keywords: Demand Response, Load Optimization, MATPOWER, Load Flow, Demand Side Management

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List of Abbreviations

DSM	Demand Side Management
DR	Demand Response
EDR	Economic Demand Response
ERCOT	Electric Reliability Council of Texas
kV	Kilo Volts
kW	Kilo Watt
LF	Load Flow
PJM	Pennsylvania-New Jersey-Maryland
SLD	Single Line Diagram
TXN	Transmission

Chapter 1
Introduction

This chapter gives a brief overview of Demand Response, its difference with respect to Supply Side Management, and motivation of the study with Objectives of this thesis. Moreover, a figurative flowchart of the thesis has been included as well.

1.1 Demand Response

Federal Energy Regulatory Commission (FERC) has officially defined demand response (DR) as:[1] "*Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.*"

In addition to, Demand Response includes all planned alterations to consumption arrangements of electrical energy to persuade customers that have agreed to modify the time of usage, scale of kW demand, or the total electricity utilization.[2]

Moreover, Demand Response (DR) can be also be expressed as "a wide range of actions which can be taken at the customer side of the electricity meter in response to particular conditions within the electricity system (such as peak period network congestion or high prices)".[3]

By design, DR is a program to

- Either limit or distribute peak electricity demand or
- Avoid or alleviate power system contingencies (i.e. act as Spinning Reserve)

Whatever the application, the fundamental purpose of DR is to involve clienteles in adjusting their usage in response to control signals. [4]

An area of active research, DR is considered a vital part of future smart grid initiatives. Other include, but are not limited to, increasing energy efficiency across the power system spectrum, enabling smart home and building management systems, integration of distributed energy sources and proliferation of EVs. [5] and [6]

Energy efficiency is dissimilar to DR as the former is a concept to deliver results with less energy usage. Moreover, in electricity power systems, DR is nearly analogous to dynamically managing customer demand to control usage of electricity taking into account the supply conditions. This may include having electricity consumers decrease their electrical load at either to receive monetary benefits or during contingency situations.[7] Only difference is that dynamic demand systems passively react to stresses in power systems whereas DR can involve switching over to another supply ((if available) or limit electricity consumption.[8] Differences, however, remain little and sometimes the terms are used (incorrectly) interchangeably.

Generally, demand response is further classified as

- Emergency or reliability-based demand response (EDR)
- Economic or price-based demand response and
- ancillary services demand response.[9]

Briefly elaborating on each of the above classifications, emergency demand response is employed when there is scarcity of supply and to prevent unplanned service interruptions. Moreover, economic demand response is a means to curtail electricity consumption at consumers’ end when cost charged increases. However, it is the prerogative of the consumers to decide whether the tradeoff of decreasing electricity is worth it or not. Lastly, ancillary services demand response is employed to ensure the quality of electricity supply remains acceptable and transmission and distribution system behaves within the secure limits. Traditionally, electricity generators have provided this service to maintain secure power system operation.

At present, DR schemes are executed at consumer end using specified control systems that shed load whenever there is a request from the electric utility, or the price of energy is increased. Various services such as lighting fixtures, washing machines or air conditioners, are switched off according to a predefined merit order whenever there is a situation that merits application of DR. In some very specific cases, DR is not an option as load is too critical to be shed. In such cases, an onsite generator is switched on when the utility wished to execute DR and the grid- access of the facility is removed.

1.2 Demand Side Management (DSM) vs Supply Side Management

In modern electricity markets, most of which are deregulated, electricity distribution companies maximize their operational profits be bidding for electricity distribution prices. These prices, in addition to, do not stay same and fluctuate in response to several factors such as real-time electricity demands. In short, electricity prices and demand are positively corelated and a rise in demand will generally raise the electricity prices as well. Hence, to ensure constant power supply while staying on the profitable side of electricity trading, a prudent power system management is necessary. This management of power systems is classified into supply-side management and demand-side management (DSM).

Briefly, supply-side management aims to increase the operational efficiency of electricity generation, transmission and distribution [11]. Some advantages of this conventional power system management include:

- consumer value is maximized as energy production is efficient and at the minimum economic cost;
- without resorting to expensive investments in new infrastructure, electricity demand can be met satisfactorily; and
- minimizing environmental impacts through the efficient operation of power system assets.

However, since the supply-side management is chiefly applicable on thermal power plants, variation in fuel prices negatively affect its efficacy. This is where the DSM shines as it is not affected by volatility of fuel prices and is ultimately more advantageous for the all agents involved in an electric power market Hence, DSM becomes more beneficial than supply-side management as electricity demands continue to grow at a rate that exceeds the expansion rate of power systems.

1.3 Motivation

Smart Electricity Grid is the focus of intensive research and development. Integration of renewable energy is on the rise and techniques such as DR are expected to become ubiquitous in managing the system in an optimal and reliable manner. This research targets the implications of one of the corner stones of a future smart grid (i.e. demand response). It is expected that results of this study will result in an evolved understanding of various relatively unexplored facets of demand response (location, magnitude and composition) and form the basis for optimal demand response activation in a future smart grid.

The reliability of Pakistan's power system is questionable owing to low efficiency of the generation fleet. Demand response is a novel concept, being used to provide reliability-based services in many jurisdictions such as *Pennsylvania-New Jersey-Maryland* (PJM) and *Electric Reliability Council of Texas* (ERCOT). The application of demand response techniques to provide reliability-based reserves in a secure manner on Pakistan's power system, can mitigate generation outage-based blackouts and result in significant savings to the economy by mitigating the cost of unavailable supply.

Electrical Utilities and System Operators can utilize this research as guideline in progression towards a secure transition towards a more pro-active approach to demand-generation imbalance management.

Extensive research in DR has given rise to the expectation that this technique will be used to decrease on-peak electricity consumption as well [10].

Hence, demand response can be a more cost-effective alternative than adding generation capabilities to meet the peak and or occasional demand spikes.

There is increasingly a technique being used in DR where the load is increased instead of being shed and is used to match generation at an instance where demand is lower. Some market operators may thereby encourage energy storage to arbitrage between periods of low and high demand (or low and high prices).

1.4 Objectives

- To perform sensitivity analysis to determine the Transmission System impact of Demand Response with respect to load composition, magnitude and location.
- To suggest a DR load optimization strategy in terms of magnitude, composition and location.

1.5 Methodology

A figurative flowchart for this thesis is as follows. A conjecture formed regarding the impact of DR on bus voltages of high voltage transmission system. This conjecture was supported by a literature review and research gaps were identified, which were used to modify the conjecture. Based on the material available during the literature review, a methodology was devised. Moreover, this all was implemented on MATPOWER IEEE test cases. The results were analyzed with special focus on bus voltages and how they were behaving in response to change in certain factors.

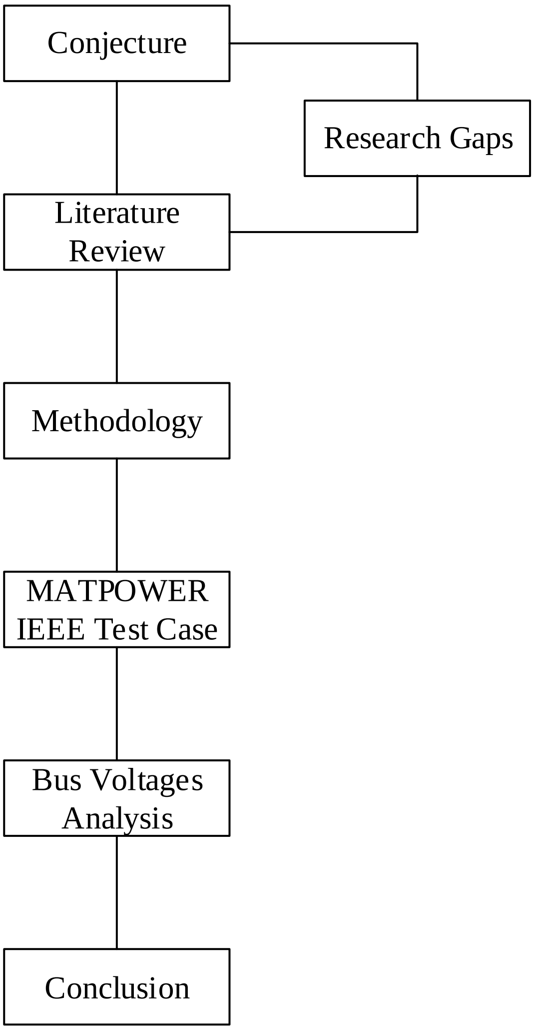

Figure 1: Figurative Flowchart

1.6 Summary

This chapter gives a brief overview of Demand Side Management (DSM) and compares it with Supply Side Management. A subclassification of DSM, referred to as Emergency Demand Response, is focus of this thesis. EDR is used when there is a contingency in the system and there is a scarcity of supply. This EDR has been applied to IEEE test cases and voltage magnitude have been recorded after performing Load Flow. DSM or EDR is a cornerstone of smart grid paradigm and its importance and applications are set to increase. Hence, this thesis is an invaluable tool for power system planners.

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Chapter 2
Literature Review

This chapter presents an overview of relevant literature related to the power system stability in general and voltage stability in particular. A comprehensive background on DSM is also discussed in context to its application in modern power systems.

2.1 Power System Stability

Power system stability can be defined as the ability of an electrical power network to recuperate a steady-state operating equilibrium in response to a disturbance, provided an initial operating state is specified. In addition to, it is also desirable that all or most of the power system variables remain bounded at the end of the disturbance period so that the entire electrical system is considered integrated and intact [1] and [2].

Disturbances are physical in nature and include either or some or all of the following:

- Faults in any part of the system
- Changes in load magnitude, location or composition (i.e. power factor)
- Generation outages
- Transmission and distribution lines outage
- Voltage collapse

Whereas, the variables mentioned earlier can also be several but for this thesis, they are limited to:

- Voltage Magnitude
- Voltage Angle
- Current Magnitude
- Frequency

Power system stability is a huge topic and field, but we will be broadly classifying it into

- Voltage Stability
- Rotor Angle Stability
- Frequency Stability

In addition to, further sub-classification, for each of the above-mentioned stabilities, is considered based on whether the disturbance is short term or long term, and if it is a small or a large disturbance. This classification scheme is depicted in Figure 2 [2].

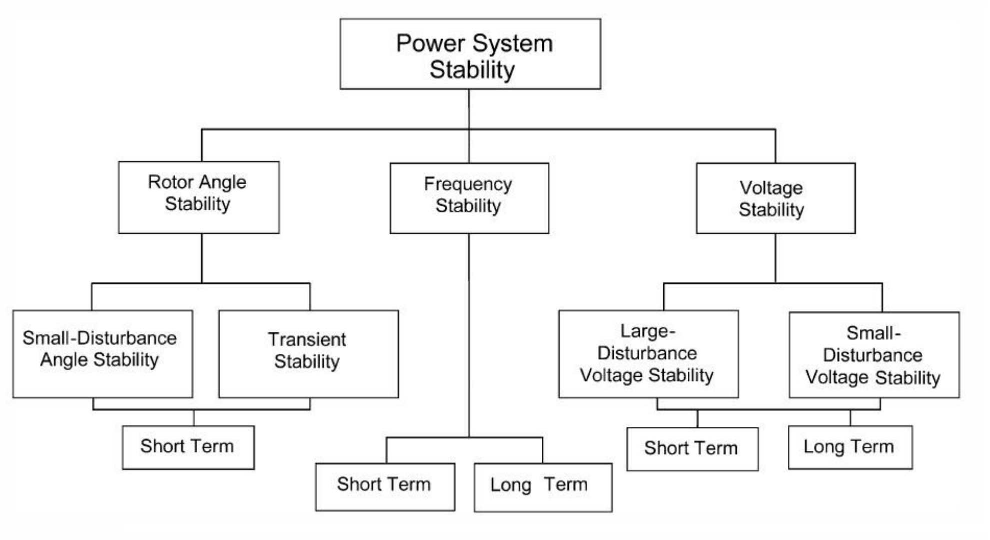

Figure 2: Power System Stability

For this thesis and research endeavor, we have only focused on the Voltage Stability aspect as it is a significant measure of the health of an electric power system and an important tool employed by utilities, system planners and system operators.

2.1.1 Voltage Stability

Voltage Stability is defined as the capacity of a system to sustain steady-state voltage levels at all the buses when a disturbance event is initiated. Based on the nature of disturbance it is either large-disturbance voltage stability or, conversely, a small-scale voltage stability. Based on the nature of disturbance, voltage stability phenomenon can either be long-term or short term which is different from angle stability. [3] and [4] For example, a short-term stability event will be in the range of 10-20s and can be some voltage fluctuations that occur due to induction motors or electric drives i.e. devices that are considered fast-acting. Conversely, if variation in voltage is caused by disturbances that occur over a longer period of time e.g. from 1min to several minutes than this stability is classified under the long-term stability. Such variations include slow variation in load, transmission and distribution lines overloading, tap-changing in transformers and generators unable to supply enough reactive power limits.

Voltage stability and angle stability differ mainly due to the difference of balance between power demand and generation. Voltage stability is affected by the reactive power demand and generation balance whereas, angle stability is dependent on the balance of real power demand and generation.

Furthermore, another important aspect of voltage stability phenomenon is that disturbances can cause both local and regional stability issues. It can be a local phenomenon only as a single bus or a connected group of buses may have voltage stability issues and may not affect the entire system. Or it can be a global issue in which several buses simultaneously undergo voltage stability issues and cause a rotor angle stability scenario which than affects whole system. It has been found that some voltage stability issues initially are a localized issue but then escalate to affect the whole power system.

2.1.1. Basic Concept of Voltage Stability

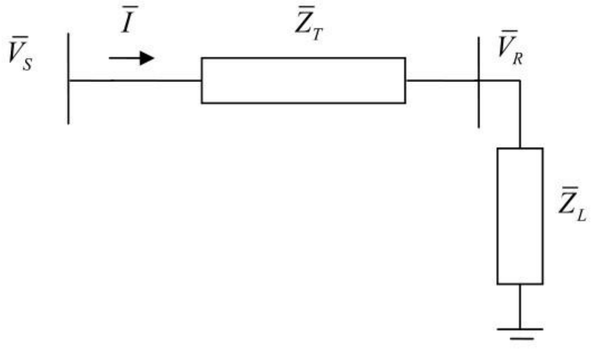

Figure 3: Single-Line-Diagram of 2 Bus System

We can use the Figure 3 to comprehend the concept of voltage stability numerically. Figure represents a Single-Line-Diagram (SLD) of a two-bus system. One of the bus is intended as a sending end, and its voltage is represented by $\mathbf{V_S}$, whereas the $\mathbf{V_R}$ represents the other receiving end voltage. The transmission line connecting these buses is denoted by a short-line with an impedance $\mathbf{Z_T}$ such that $\mathbf{Z_T}<\theta_T$.

Consider a load with an impedance $\mathbf{Z_L}$ such that $\mathbf{Z_L}< \theta_L$ is attached to the bus at the receiving end. We can calculate the magnitude of transmission line current **I** according the equation [x] in which the sending-end bus voltage is taken as reference.

$$|\boldsymbol{I}| = |\frac{\boldsymbol{V_S} < 0}{\boldsymbol{Z_T} < \boldsymbol{\theta_T} + \boldsymbol{Z_L} < \phi_L}| = \frac{\boldsymbol{V_S}}{\sqrt{\boldsymbol{Z_T^2} + \boldsymbol{Z_L^2} + 2\boldsymbol{Z_T}\boldsymbol{Z_L}\,cos(\theta_T - \phi_L)}}$$

We can rearrange the equation and substitute to express magnitude of receiving-end voltage **V_R** as

$$\boldsymbol{V_R} = \frac{\boldsymbol{V_S Z_L}}{\sqrt{\boldsymbol{Z_T^2} + \boldsymbol{Z_L^2} + 2\boldsymbol{Z_T Z_L}\cos(\theta_T - \phi_L)}}$$

Furthermore, we can find the load consumption of real (denoted by **P_L**) and reactive power (denoted by **Q_L**) as

$$\boldsymbol{P_L} = \frac{\boldsymbol{V_S^2 Z_L}\cos(\phi_L)}{\sqrt{\boldsymbol{Z_T^2} + \boldsymbol{Z_L^2} + 2\boldsymbol{Z_T Z_L}\cos(\theta_T - \phi_L)}}$$

$$\boldsymbol{Q_L} = \frac{\boldsymbol{V_S^2 Z_L}\sin(\phi_L)}{\sqrt{\boldsymbol{Z_T^2} + \boldsymbol{Z_L^2} + 2\boldsymbol{Z_T Z_L}\cos(\theta_T - \phi_L)}}$$

We can draw a P-V Curve to demonstrate the relation between receiving-end voltage **V_R** and real power consumption of load, **P_L**. Assuming the sending-end bus voltage **V_S** and transmission line impedance **Z_T** to be 1pu and 0.25pu respectively. These values were chosen as they represent a typical power system configuration as reactance-to-resistance ratio is high in a power transmission system. If we keep the power factor of the load constant at 0.8 and decrease the impedance of the load **Z_L** we can increase load consumption of power (both real and reactive). Moreover, the receiving-end voltage plotted against the consumption of real power by the load will yield a P-V Curve as shown in Figure 4.

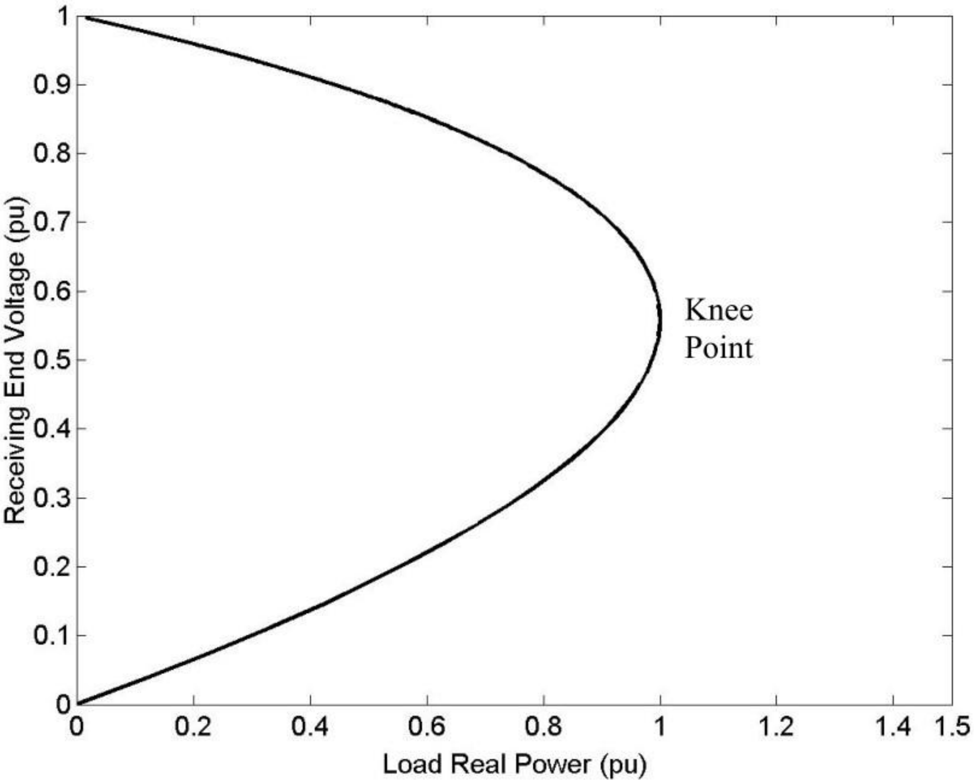

Figure 4: P-V Curve

This curve tells us that as the load rating increases from no-load value, and power consumption increases, the receiving-end voltage $\mathbf{V_R}$ decreases from initial 1pu to lower value. This happens because as the real-power consumption at load-end increases so does the magnitude of current **I**. Reason for this is that voltage-drop from sending to receiving end, caused by transmission line impedance $\mathbf{Z_T}$, is less than the increase in current. As shown in Figure 4, maximum real-power consumed by the load will be 1pu and it will be at the condition when $\mathbf{Z_T = Z_L}$. However, any lower decrease in value of load-impedance $\mathbf{Z_L}$ mean that line current will increase but that increase will be less than the drop in receiving-end voltage. Combined effect of this translates into that real-power consumption by the load will decrease. As observed from the Figure, this point is the inflection of the curve and is referred to as Knee-point or Critical-power point or Maximum-Power-Transfer point. As the operating point goes past this point, decreasing load-impedance is not advisable as such act will decrease the power consumption and increase losses.

2.1.1.2 Effect of Load Type on Voltage Stability

In continuation of previous section, effect of varying load type on Voltage Stability is discussed in this section. Consider the P-V curve in Figure 5, it is evident that there are two distinct possible receiving-end voltages for a particular value of real-power consumption. For example, at 0.6pu there will be two receiving-end voltages of 0.2pu and 0.85pu respectively, as referenced in the figure with points of A and B.

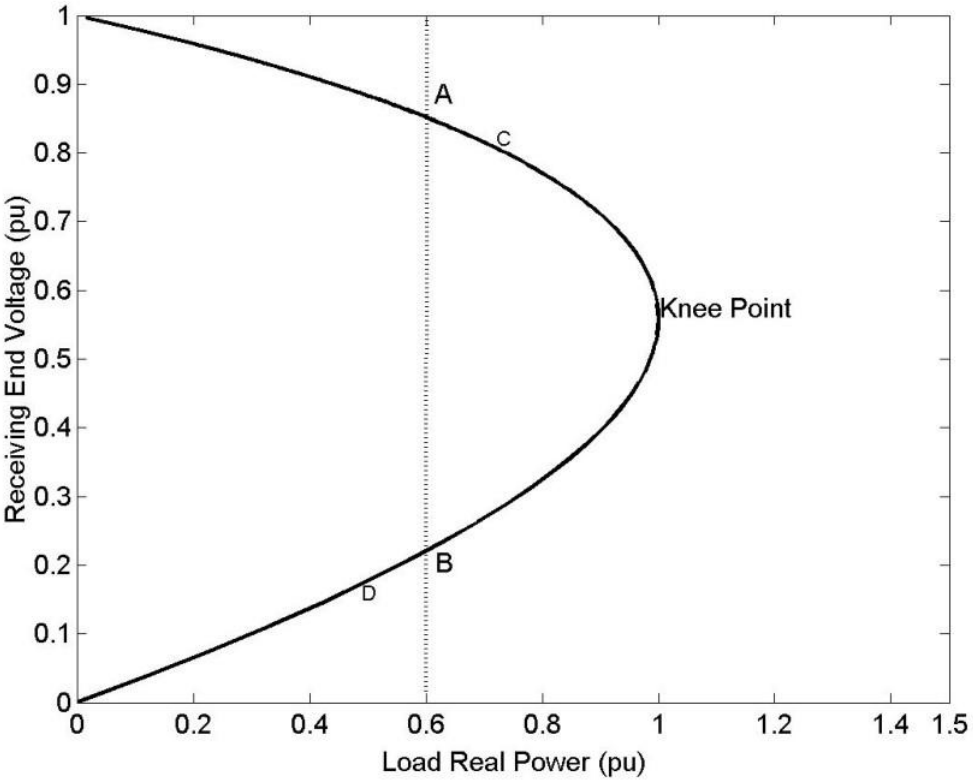

Figure 5: P-V curve with stable and unstable operating points

Constant MVA Load

If we assume that the load is a Constant-MVA Load i.e. has a reactive power requirement that will not vary, then then any point above the knee-point is stable and vice versa i.e. unstable below the knee-point. Hence, on Figure 5 A operating point is stable, and B is unstable. To elaborate more, assuming that some disturbance occurs and the operating point shifts to C i.e. there is a change in power consumption and voltage levels, as evident from the Figure 5 real power is drawn more at C. At higher real-power, current flow will decrease (and voltage drop will also be less) because the is constant-MVA. This leads to operating point oscillating from C to A and eventually dampen down to stay at A, leading to a stable voltage level and power system. However, for operating-point at B the system is unstable. To elaborate, in case of a disturbance the operating point will shift to D and real power will also decrease and be lower than at B. Decrease in real power leads to increase in line current (since it is a constant MVA load), which, in turn, causes a further decrease in voltage levels. This cycle continues till the receiving-end voltage is 0. Such scenario is typical of a Voltage Collapse situation. Hence, B operating point is unstable.

We can further observe from the Figure 5 that receiving-end-voltage and power consumed-by-load gradient i.e. dV_R/dP_L is different for curve above and below the knee-point. For P-V curve above the knee point, dV_R/dP_L is negative which translates to that variation in voltage and real power are opposite to each other i.e. an increase in power causes a decrease in voltage and vice versa. Therefore, below the knee-point, $dV_R/dP_L$is positive and zero at knee-point itself.

Varying Load Power Factor

Generalizing this response to cover loads with different power factors, we can observe from Figure 6 that load power factor shift from lagging to leading causes the knee point to move towards high-real-power and high-voltage coordinates. Which essentially means that voltage stability will improve as we shift the load power factor from lagging to leading. The converse of this is also true. Reason for this shift is due to change in magnitude of line current and subsequent voltage drop.

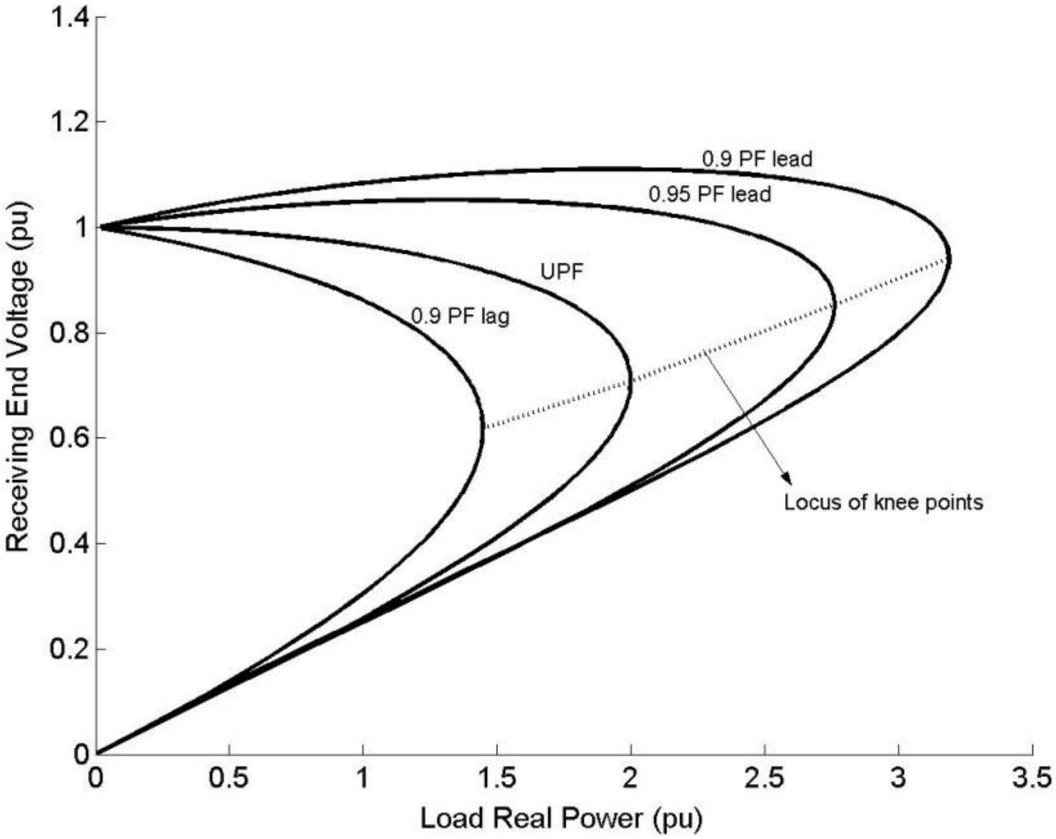

Figure 6: P-V Curve for different power factor loads

2.1.2 Q-V Curve

To understand the relationship of load reactive power consumption and receiving-end voltage, we can plot a Q-V Cure for varying load impedances but keeping the reap-power consumption of load constant. This curve, as represented by Figure 7, shows, for three distinct load power factors, the variation of receiving-end voltage versus change in load reactive power.

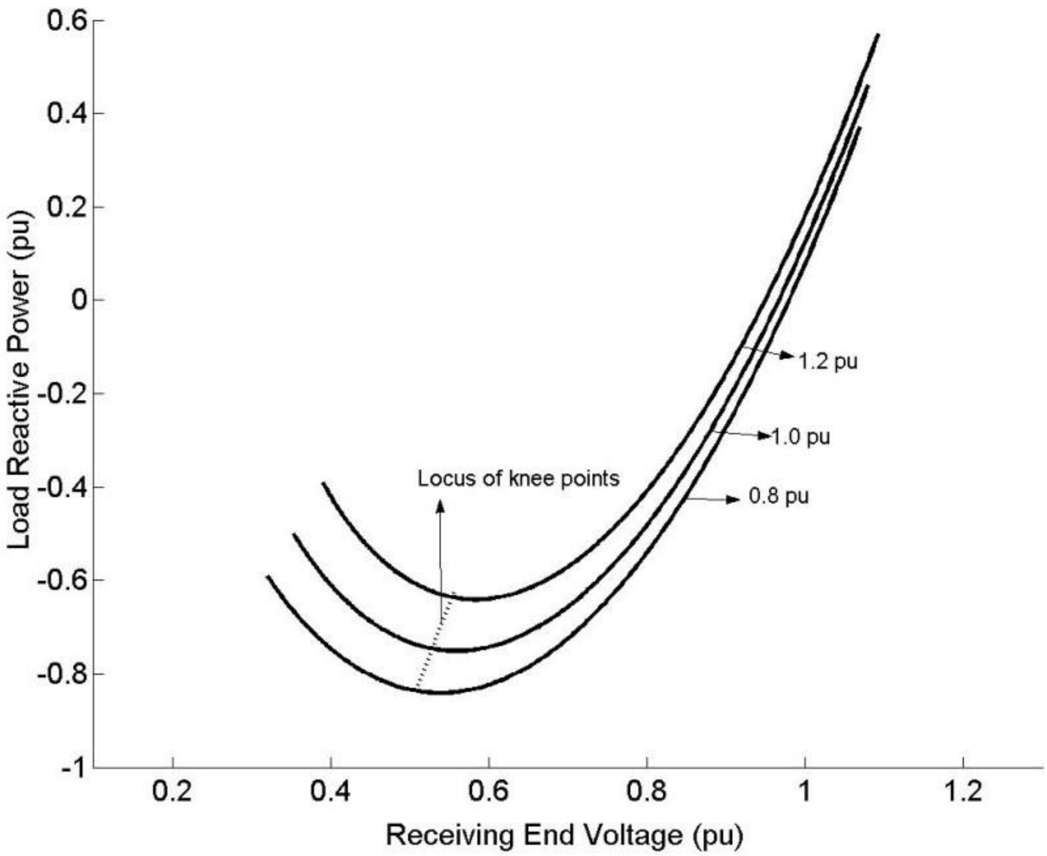

Figure 7: Q-V Curves for different load real powers

We can divide the curve into regions with stable or unstable nature of power system, similar to the P-V curve. Knee points are grouped via their locus and illustrated on the Figure. On the left of this locus, the curve has dQ_L/dV_R that is negative and whole region is classified as unstable. Negative gradient means that reactive power and receiving-end voltage are inversely proportional to each other. On the other hand, region right to the locus represents a stable system as dQ_L/dV_R is positive and reactive power and voltage at receiving end are proportional to each other.

Another aspect of the unstable portion of the curve is that receiving-end voltage will not improve despite the addition of a shunt-capacitance from some source. We can determine the voltage stability of a system by individually checking each bus for sensitivity to receiving-end voltage with respect to reactive power compensated. The operating point will be considered stable if the sensitivity is positive and a particular bus lies on the region on the right of knee point locus. Vice versa will be true as well.

A point of caution, this stability assessment is only suitable for loads that are considered constant MVA as other types of loads (constant current and constant impedance) interact differently with the system and settle at a new operating point but this area is not under discussion in this thesis.

2.2 Brief Overview of Demand Side Management (DSM)

DSM is a modern technique that is implemented in some markets by market entities to encourage the use of tools and techniques that are beneficial to all market participants such as generators, grid operators, distribution companies and end consumers [5]. Some practices performed under DSM are aimed at modifying the electrical load shapes by influencing end use consumers [6]. As a result of these practices, the complexity of power system increases manifold because there is an added layer of monitoring and measuring electrical loads, generators and transmission lines [7]. This, as a result, increases the implementation of DSM. However, the potential benefits of DSM are believed to outweigh any drawbacks in the form of incurred financial costs.

Moreover, with respect to classification of DSM, Figure 8 shows that DSM can be subdivided into

- energy efficiency,
- demand response (DR) and
- strategic load growth.

For this thesis, we are only focusing on Demand Response (DR) and particularly its subtype Emergency Demand Response (EDR). EDR can be defined as a form of DR where the contingencies and scarcity of supply are counted by employing DR to ensure the integrity of electric power system.

In addition to, DR is normally employed [5] via

- peak clipping,
- valley filling,
- load shifting or
- any combination of these as seen fit.

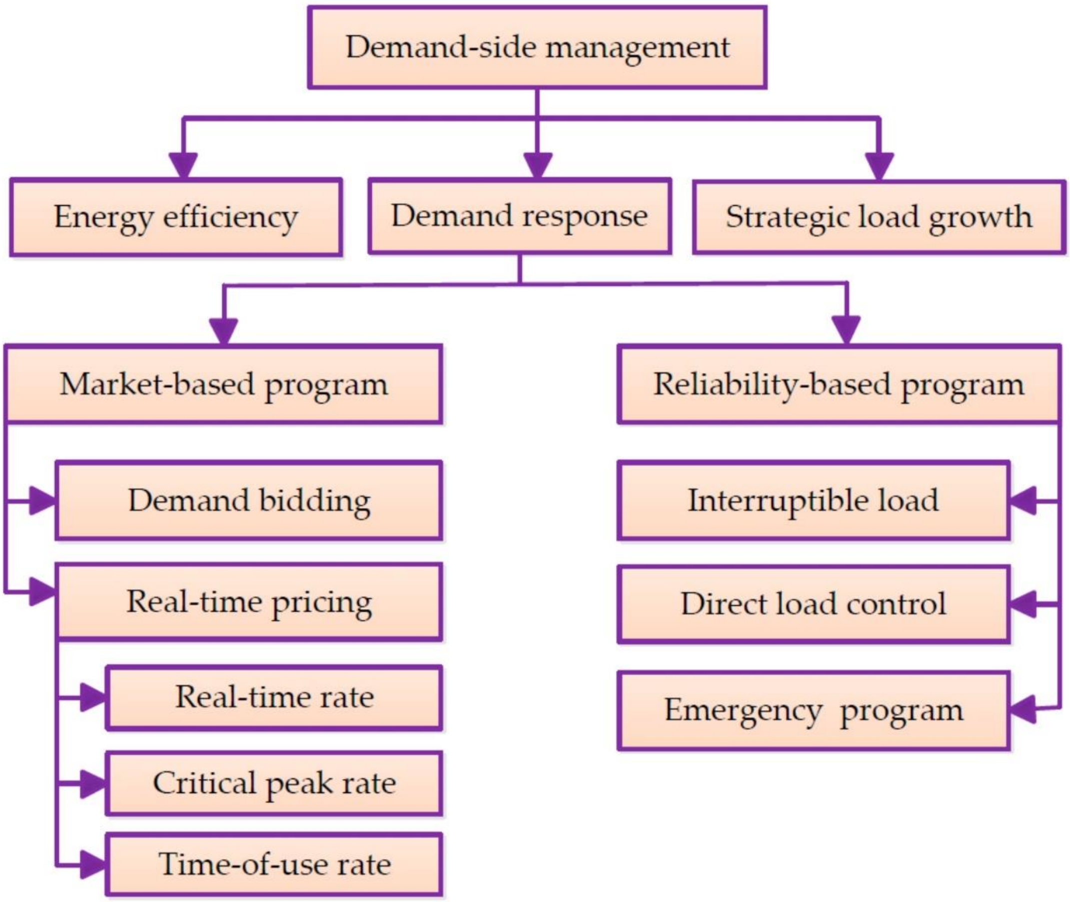

Figure 8: Demand Side Management (DSM) Techniques [8]

2.3 Impacts of DR on Power System Operations

Application of DR/DSM on the operations of power systems is an ongoing topic of active research. Some aspects are, however, of particular interest to engineers and scientists. These include

- Voltage Stability
- Frequency Stability
- Transmission Congestion
- Preventive Maintenance
- Facility Upgrade
- Renewable Energy Resources
- Power System Flexibility

However, for the purpose of this thesis we are only concerned with impacts of DR w.r.t Voltage Stability. This was chosen because voltage levels at buses are a vital indication of the health of a power system and grid operators actively lookout for keeping the voltage levels within the limits specified in grid codes. Briefly speaking, voltage stability refers to the ability of power systems to maintain acceptable voltages (usually ±5% of the base voltage of TXN systems) at all buses under normal operating conditions (i.e. N-0 condition) and after disturbances [2]. This metric has also been proved as the ability of DR to alleviate TXN congestions by keeping the voltage levels stable thereby saving important financial investments [9]. Although not the topic of this thesis, DR application can also keep the frequency in check as wel [10].

Many studies have focused on the load control techniques of DSM [11], the roles of DSM in the electricity market [12], the economic benefits of DSM [13], the impacts of DSM on the industrial and residential sectors [14] and [15], the interactions of DSM with other smart grid technologies [16], the business models of DSM [17], the impacts of DSM on power system reliability [18], the optimization techniques of DSM [19] and [20] and the load forecasting and dynamic pricing schemes of DSM [21]. Moreover, DSM has been implemented with promising outcomes in various countries, such as the UK, China, North America, Kuwait and Turkey.

2.4 Summary

Voltage Stability aspect as is a significant measure of the health of an electric power system and an important tool employed by utilities, system planners and system operators. Voltage stability, amongst other factors, is a result of imbalance of reactive power generation and demand and hence affected by DR application viz-a-viz its location, magnitude and composition.

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Chapter 3
Methodology

This chapter introduces the methodology to analyze bus Voltage levels when DR is applied at a load bus in an electric power system. Analysis techniques are discussed and step-by-step guidelines are mentioned.

3.1 Analysis

We can analyze the voltage stability of a system by two techniques

- Static Analysis
- Dynamic Analysis

We consider only the algebraic equations related to power system when performing static analysis of the system and is suitable for analyzing effects of small disturbances in the system. However, DAE (Differential-algebraic system of equations) are iterated and solved to gauge system stability over a longer time period when disturbances are considered larger. In addition to, load modelling is important as each type of load will have a different response on the system stability. Moreover, other parameters such as line charging capacitance (including Ferranti Effect) etc. should be considered to accurately adjudge voltage stability.

This thesis deals with Static Analysis primarily.

3.1.1 Static Analysis

During the static analysis [1] for voltage stability we consider the instances of the system in steady-state at regular intervals and for each “snapshot” we solve power balance algebraic equations and calculate desired parameters. We not only asses the voltage stability of the system but also the degree of separation between the operating point and instability.

We can use either of the following to perform static analysis.

- Sensitivity Analysis
- Modal Analysis [3]

Only sensitivity analysis has been applied for this thesis.

3.1.1.1 Sensitivity Analysis

In terms of electrical power systems, we can define this analysis as assessing whether the uncertainty, in the results or output of a mathematical model or a numerical system that approximates an electrical power network, can be divided and allocated to different sources of uncertainty in its inputs.

[2] has assumed that the power system is in steady-state. Power balance equation is given as following. Given $i = 1,2,\ldots,n$ and bus number 1 is a slack bus.

$$P_{Gi} - P_{Di}(V_i) - \sum_{j=1}^{n} V_i V_j Y_{ij} \cos(\theta_i - \theta_j - \alpha_{ij}) = 0$$

We take the balance equations for reactive power at the load buses, for

$$i = n_g + 1, n_g + 2, \ldots, n$$

$$Q_{Di}(V_i) + \sum_{j=1}^{n} V_i V_j Y_{ij}\, sin(\theta_i - \theta_j - \alpha_{ij}) = 0$$

The linearized form of equations, from X and X, is given as

$$\begin{bmatrix} \Delta P_2 \\ \vdots \\ \Delta P_n \\ \Delta Q_{n_g+1} \\ \vdots \\ \Delta Q_n \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta_2 \\ \vdots \\ \Delta\theta_n \\ \Delta V_{n_g+1} \\ \vdots \\ \Delta V_n \end{bmatrix}$$

Or

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = [J] \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix}$$

In the above equation, J matrix is the Jacobian Matrix and is used in Newton-Raphson load flow analysis to calculate power system parameters. Since real power is constant, so ΔP is zero. From equation XYZ

$$\Delta\theta = -[J_{P\theta}]^{-1} J_{PV} \Delta V$$

Substituting and simplifying results in

$$\Delta Q = \left[J_{QV} - [J_{P\theta}]^{-1} J_{PV} J_{Q\theta}\right] \Delta V$$

Let

$$J_R = \left[J_{QV} - [J_{P\theta}]^{-1} J_{PV} J_{Q\theta}\right]$$

Then

$$\Delta V = J_R^{-1} \Delta Q$$

Sensitivity is represented by the matrix J_R^{-1}, which is in fact the gradient of Q-V Curve. As mentioned earlier, positive value sensitivity means the system is stable and vice versa. Moreover, closer the value to zero, more stable or unstable the system is as compared to a sensitivity with a larger distance from zero.

The analyses were repeated with the addition of a shunt capacitor to simulate the presence of a highly capacitive load source.

3.2 MATPOWER

MATPOWER [4] is a powerful open source MATLAB/Octave programming package providing for load flow and optimal power flow. For this thesis, only load flow was used. Moreover, there are numerous test cases that are packaged with this tool. For this thesis, IEEE Test Case of 5 Bus, 9 Bus and 39 Bus were used. Since, these test cases are in a .m file, the electrical system parameters for modified as required.

3.3 Methodology (Without Shunt Capacitor)

1. Selection of networks with base voltage in excess of 230kV from test cases available in MATPOWER.

2. Reduction in electrical power generation to simulate a power outing and subsequent reduction in electrical loads to simulate balancing via DR.

3. For each network, a DR ‘step’ was selected. Generation-Loads were reduced in multiple steps and load flow was performed on each step and Bus Voltages were calculated.

4. The analyses were repeated with the following load power factors

    a. Loads with > 0.9PF

    b. Loads with PF in the range: 0.5<PF<0.6

3.4 Methodology (With a Shunt Capacitor)

An analysis was performed on two IEEE systems i.e. 5 Bus and 9 Bus, in order to enhance the observable effect of Bus overvoltage caused by application of DR. This has been executed via the following procedure

- A load bus was selected that has (1) No Generator attached to it and (2) Where possible, is adjacent to buses and generators attached to them. Rationale behind this is to try to isolate the effects of DR application to a certain region. This will enable to limit the effect of DR on other buses in the system except our targeted load bus.
- Load power factor was changed to be between 0.5PF and 0.6PF. A Load Flow was performed, and bus voltages were considered to be as base case.
- A generator was removed, to simulate a contingency, and DR applied exclusively on the load bus. In case the load rating was not enough to balance the removed generator rating, DR was performed on another load bus. Care was taken to keep this value to be a minimum incases it was not completely avoidable. Load Flow was performed to calculate the bus voltages.
- A shunt capacitor was added to the targeted load bus. This was done to ensure that the voltages will increase due to the excessive reactive power and a change in voltages is more pronounced. Load Flow was performed for two values of the Capacitor i.e. 30MVAr and 90MVAr.
- This analysis was repeated with the removal of the Generators from other buses connected to the targeted load bus.

3.5 Summary

Voltage stability can be measured in a power system by implementing Load Flow which is a numerical method that gives voltage magnitude and rotor angle, amongst other variables, for further analysis. This technique is a Sensitivity Analysis technique and is itself classified under Static Analysis of power systems i.e. related to steady state operation. MATPOWER was used to perform this Load Flow technique on electrical power network with base voltage higher than 230kV. Bus voltage levels will be assessed as DR is varied with respect to its location, magnitude and composition.

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Chapter 4
Results and Discussions

This chapter contains the results of analyses performed on IEEE 5 bus system , IEEE 9 bus system and IEEE 39 bus system. These systems, along with details of loads and generators, are also listed in subsequent pages.

The analyses were repeated with the addition of a shunt capacitor to simulate the presence of a highly capacitive load and to amplify the effect of DR, to ascertain whether the presence of high reactive power (caused by Ferranti Effect) will cause breach in bus voltages at a later stage.

4.1 Introduction

DR, when applied under the DSM paradigm for making the electricity grid “smarter”, will cause high bus voltages if the composition of load and its location are such that at high DR magnitude there is increased reactive power. This will be investigated under an additional scenario as well i.e. with an addition of a shunt capacitor.

4.2 Load Flow without Shunt Capacitor

1. Selection of networks with base voltage in excess of 230kV from test cases available in MATPOWER.
2. Reduction in electrical power generation to simulate a power outing and subsequent reduction in electrical loads to simulate balancing via DR.
3. For each network, a DR ‘step’ was selected. Generation-Loads were reduced in multiple steps and load flow was performed on each step and Bus Voltages were calculated.
4. The analyses were repeated with the following load power factors
    a. Loads with > 0.9PF
    b. Loads with PF in the range: $0.5<PF<0.6$

4.3 Results for IEEE 5 Bus System

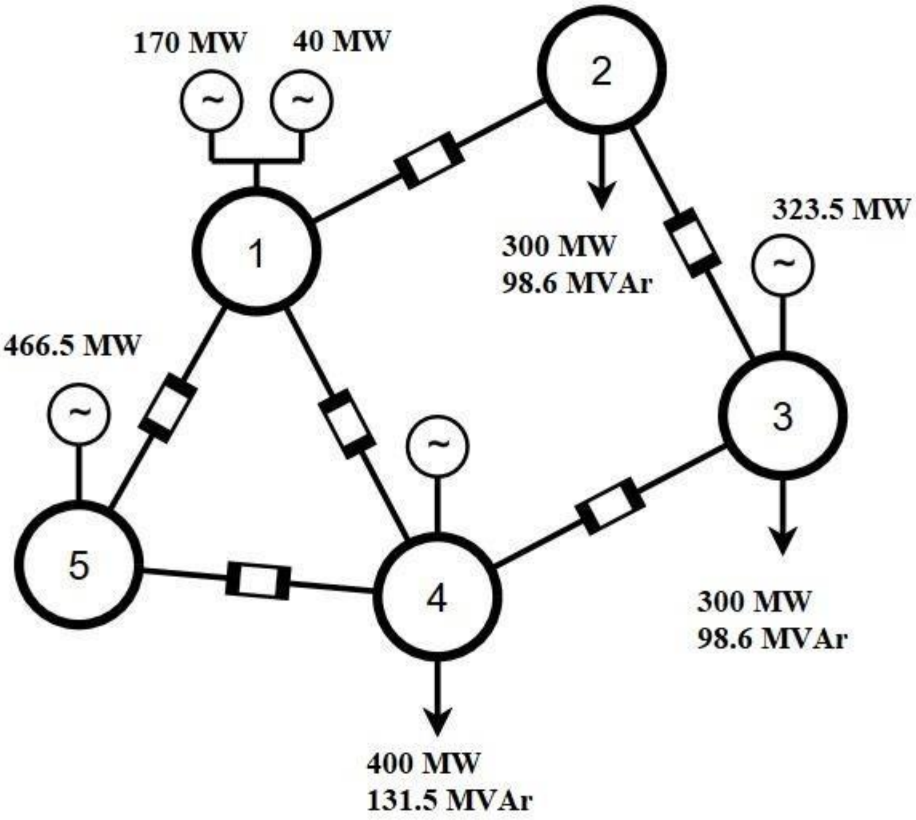

Figure 9: IEEE 5 System

- Load: 1000MW
- Base Voltage : 230kV
- DR Step: 40MW
- Maximum DR Applied (of total load): 280MW (28%)

The following table provides the sequence of Generation outage and DR active power balancing.

Table 1: Sequence (Generation Outage - DR Balancing)

Step No.	**DR**	**Gen Bus**	**Gen**	**Load Bus**	**Load**
	[MW]		**[MW]**		**[MW]**
1	0	5	466.5	2	300
2	40	5	426.5	2	260
3	80	5	386.5	2	220

4	120	5	346.5	2	180
5	160	5	306.5	2	140
6	200	5	266.5	2	100
7	240	5	226.5	2	60
8	280	5	186.5	2	20

4.3.1 Results of Load Flow when Load Power Factor is > 0.9PF

The following tables lists the Bus Voltages, when DR is applied on Load with Power Factor minimum of 0.9PF.

Table 2: Bus Voltages

DR	**Bus 1**	**Bus 2**	**Bus 3**	**Bus 4**	**Bus 5**
[MW]	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**
0	1	0.989	1	1	1
40	1	0.991	1	1	1
80	1	0.992	1	1	1
120	1	0.994	1	1	1
160	1	0.995	1	1	1
200	1	0.997	1	1	1
240	1	0.998	1	1	1
280	1	0.999	1	1	1

The following table lists the total Generation, Losses and Loads for each step of DR applied at above mentioned PF.

Table 3: Power Generation vs Power Demand and Loss

DR	**Generation**		**Losses**		**Load**	
[MW]	**[MW]**	**[MVAR]**	**[MW]**	**[MVAR]**	**[MW]**	**[MVAR]**
0	1005	371.3	5.03	50.3	1000	328.7
40	964.4	351.4	4.35	43.5	960	315.6
80	923.8	332.3	3.76	37.6	920	302.4
120	883.2	314	3.24	32.4	880	289.3
160	842.8	296.4	2.8	28	840	276.1
200	802.4	279.7	2.44	24.4	800	263
240	762.2	263.6	2.15	21.5	760	249.8
280	721.9	248.4	1.94	19.4	720	236.7

Graphs of Bus Voltages are as follows.

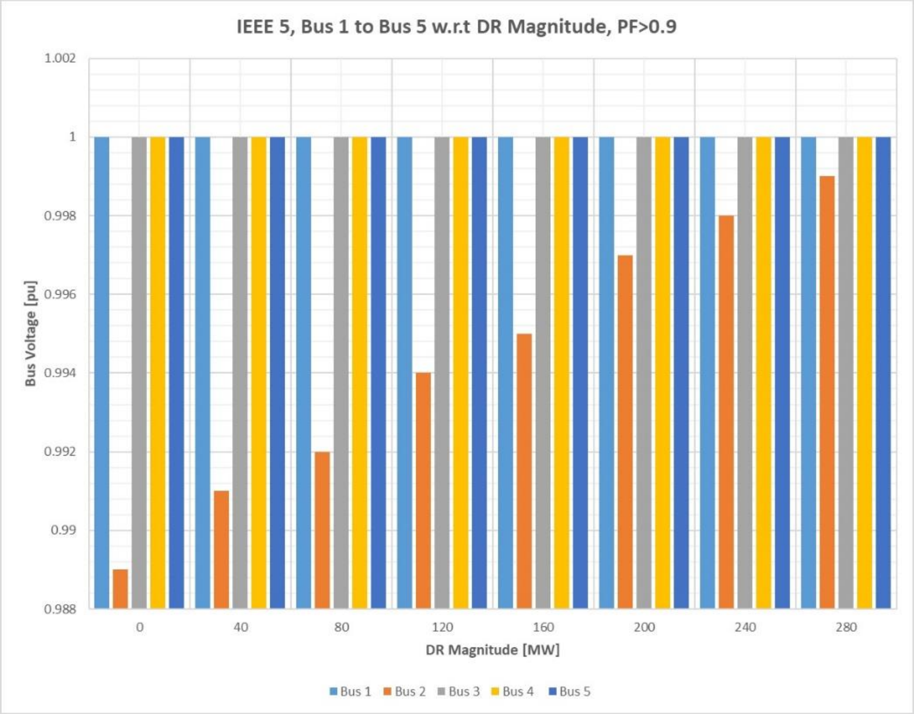

Figure 10: Bus Voltages when PF > 0.9

4.3.2 Results of Load Flow when Load Power Factor is between the range: 0.5<PF<0.6

The following table lists the Bus Voltages, when DR is applied on Load with Power Factor greater than 0.5PF but less than 0.6PF.

Table 4: Bus Voltages when 0.5< PF<0.6

DR [MW]	Bus 1 [pu]	Bus 2 [pu]	Bus 3 [pu]	Bus 4 [pu]	Bus 5 [pu]
0	1	0.96	1	1	1
40	1	0.966	1	1	1
80	1	0.971	1	1	1
120	1	0.977	1	1	1
160	1	0.982	1	1	1
200	1	0.987	1	1	1
240	1	0.992	1	1	1
280	1	0.997	1	1	1

The following table lists the total Generation, Losses and Loads for each step of DR applied at above mentioned PF.

Table 5: Power Generation vs Load+Loss

DR	Generation		Losses		Load	
[MW]	[MW]	[MVAR]	[MW]	[MVAR]	[MW]	[MVAR]
0	1006.8	745.9	6.81	68.1	1000	685.5
40	965.7	673.9	5.67	56.7	960	624.9
80	924.7	603.4	4.68	46.8	920	564.2
120	883.8	534.2	3.85	38.5	880	503.4
160	843.2	466.7	3.16	31.6	840	442.7
200	802.6	400.4	2.62	26.2	800	381.9
240	762.2	335.7	2.22	22.2	760	321.2
280	721.9	260.5	1.95	19.5	720	260.5

Graphs of Bus Voltages are as follows.

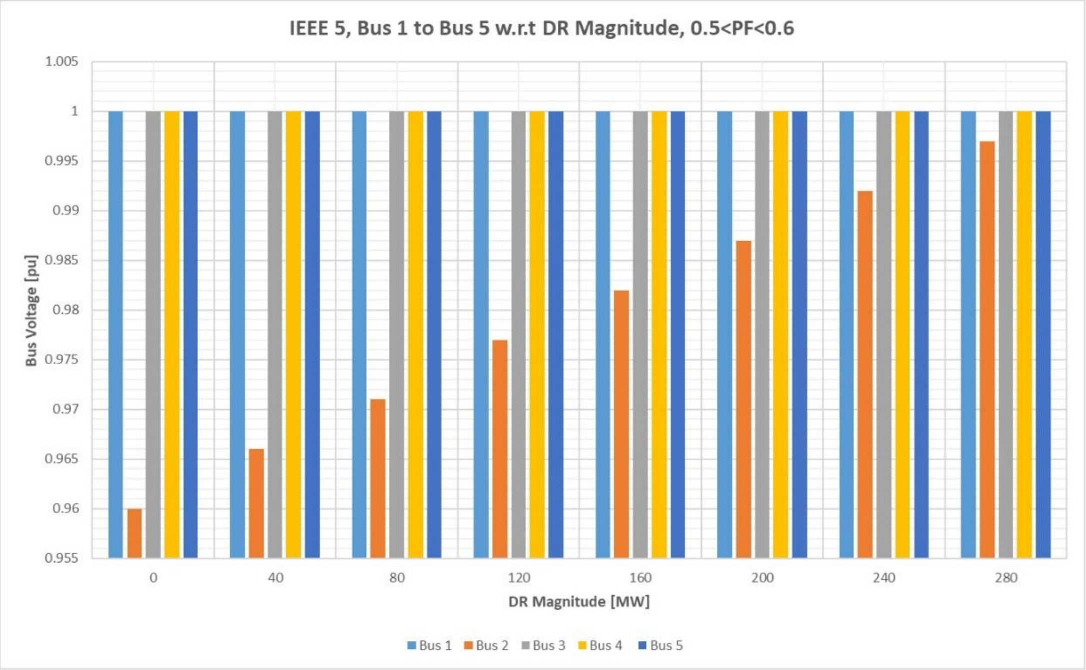

Figure 11: Bus Voltages when 0.5<PF<0.6

4.3.3 Comparison of Bus Voltages at different DR Power Factor

The following table and graph represent a comparison between Bus Voltages when DR Load is different for Bus 2 and is intended for a representation of general trend.

Table 6: Bus 2 Voltage at Different PF vs DR

DR	Bus 2 (0.5PF)	Bus 2 (0.9PF)
[MW]		
0	0.96	0.989
40	0.966	0.991
80	0.971	0.992
120	0.977	0.994
160	0.982	0.995
200	0.987	0.997
240	0.992	0.998
280	0.997	0.999

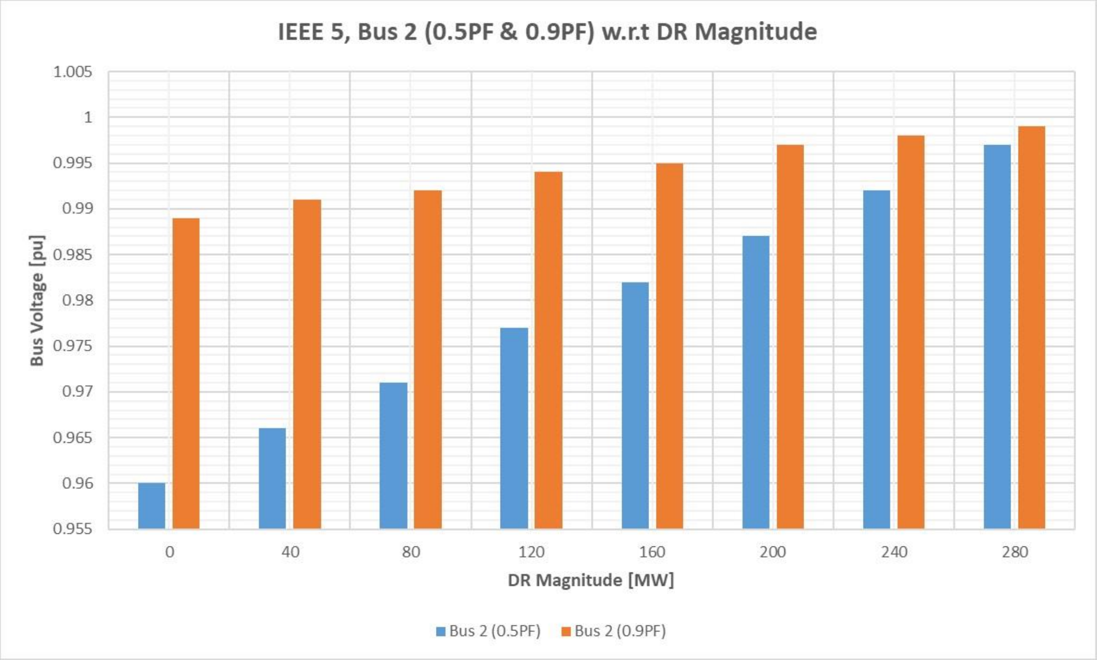

Figure 12: Bus 2 Voltage at Different PF vs DR

4.4 Results for IEEE 9 Bus System

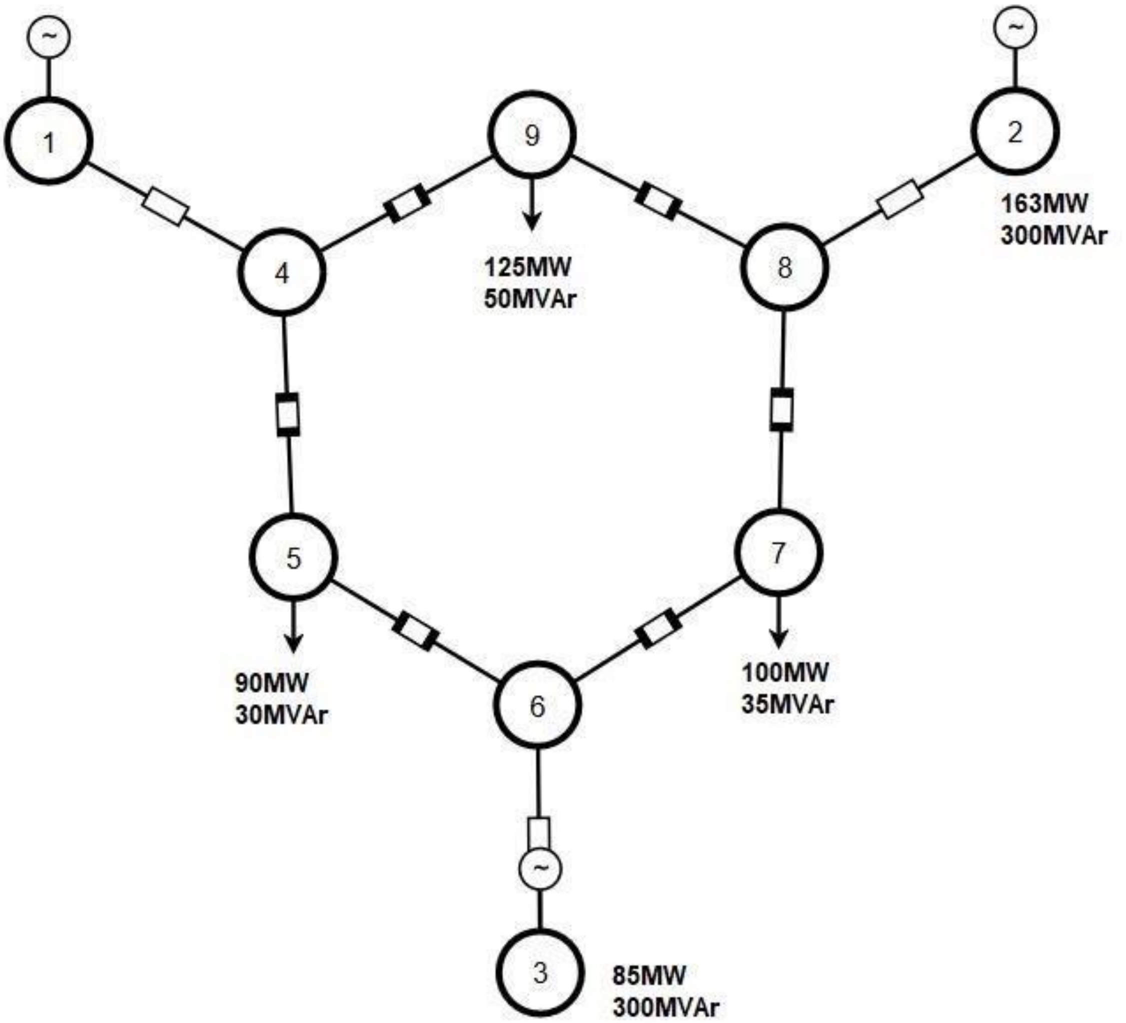

Figure 13: IEEE 9 Bus System

- Load: 315MW
- Base Voltage : 345kV
- DR Step: 13MW
- Maximum DR Applied (of total load): 234MW (74.3%)

The following table provides the sequence of Generation outage and DR active power balancing.

Table 7: Sequence of Generation Outage and DR Application

Step No.	DR	Gen Bus	Gen	Load Bus	Load
	[MW]		[MW]		[MW]
1	0	2	163	9	125
2	13	2	150	9	112
3	26	2	137	9	99
4	39	2	124	9	86
5	52	2	111	9	73
6	65	2	98	9	60
7	78	2	85	9	47
8	91	2	72	9	34
9	104	2	59	9	21
10	117	2	46	9	8
11	130	2	33	7	87
12	143	2	20	7	74
13	156	2	7	7	61
14	169	3	72	7	48
15	182	3	59	7	35
16	195	3	46	7	22
17	208	3	33	7	9
18	221	3	20	5	77
19	234	3	7	5	64

4.4.1 Results of Load Flow when Load Power Factor is > 0.9PF

The following tables lists the Bus Voltages, when DR is applied on Load with Power Factor minimum of 0.9PF.

Table 8: Bus Voltage for IEEE 9 Bus System w.r.t DR at 0.9PF

DR	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6	Bus 7	Bus 8	Bus 9
[MW]	[pu]	[pu]	[pu]	[pu]	[pu]	[pu]	[pu]	[pu]	[pu]
0	1	1	1	0.987	0.975	1.003	0.986	0.996	0.958
13	1	1	1	0.99	0.978	1.004	0.988	0.999	0.966
26	1	1	1	0.994	0.981	1.005	0.989	1.001	0.975
39	1	1	1	0.997	0.984	1.006	0.991	1.003	0.983
52	1	1	1	1	0.986	1.007	0.992	1.004	0.99
65	1	1	1	1.002	0.989	1.008	0.994	1.006	0.997
78	1	1	1	1.005	0.991	1.009	0.995	1.007	1.004
91	1	1	1	1.008	0.993	1.009	0.996	1.008	1.011
104	1	1	1	1.01	0.995	1.01	0.996	1.009	1.017
117	1	1	1	1.012	0.997	1.01	0.997	1.01	1.023
130	1	1	1	1.013	0.998	1.012	1.001	1.012	1.024
143	1	1	1	1.013	0.998	1.013	1.006	1.013	1.025
156	1	1	1	1.014	0.999	1.015	1.01	1.015	1.026

169	1	1	1	1.014	1	1.016	1.014	1.017	1.027
182	1	1	1	1.015	1.001	1.017	1.019	1.019	1.028
195	1	1	1	1.015	1.002	1.018	1.023	1.02	1.029
208	1	1	1	1.016	1.003	1.019	1.027	1.022	1.03
221	1	1	1	1.018	1.009	1.02	1.027	1.023	1.031
234	1	1	1	1.02	1.016	1.021	1.028	1.023	1.033

The following table lists the total Generation, Losses and Loads for each step of DR applied at above mentioned PF.

Table 9: Power Generation vs Load Demand+Loss

DR	**Generation**		**Losses**		**Load**	
[MW]	**[MW]**	**[MVAR]**	**[MW]**	**[MVAR]**	**[MW]**	**[MVAR]**
0	320	34.9	5	51.3	315	115
13	306.2	21.3	4.2	44.5	302	109.8
26	292.5	10	3.5	38.5	289	104.6
39	279	-1.2	3	33.4	276	99.4
52	265.5	-11.4	2.5	29.1	263	94.2
65	252.2	-20.9	2.2	25.6	250	89
78	238.9	-29.3	1.9	22.8	237	84
91	225.7	-37.5	1.7	20.7	224	78.6
104	212.6	-44.7	1.6	19.3	211	73.4
117	199.6	-51.2	1.6	18.6	198	68.2
130	186.5	-57	1.5	17.2	185	64.2
143	173.4	-63.4	1.4	16.2	172	59.2
156	160.4	-68.8	1.4	15.7	159	54.6
169	147.2	-75.8	1.2	13.6	146	50.2
182	134.1	-82.5	1.1	12	133	45.4
195	121	-88.5	1.1	11	120	40.9
208	108	-94	1	10.4	107	36.4
221	94.8	-100.2	0.8	9.1	94	32.1
234	81.6	-105.9	0.6	8.4	81	27.7

Graphs of Bus Voltages are as follows. Bus 1 to 3 are the buses with Generators attached to them.

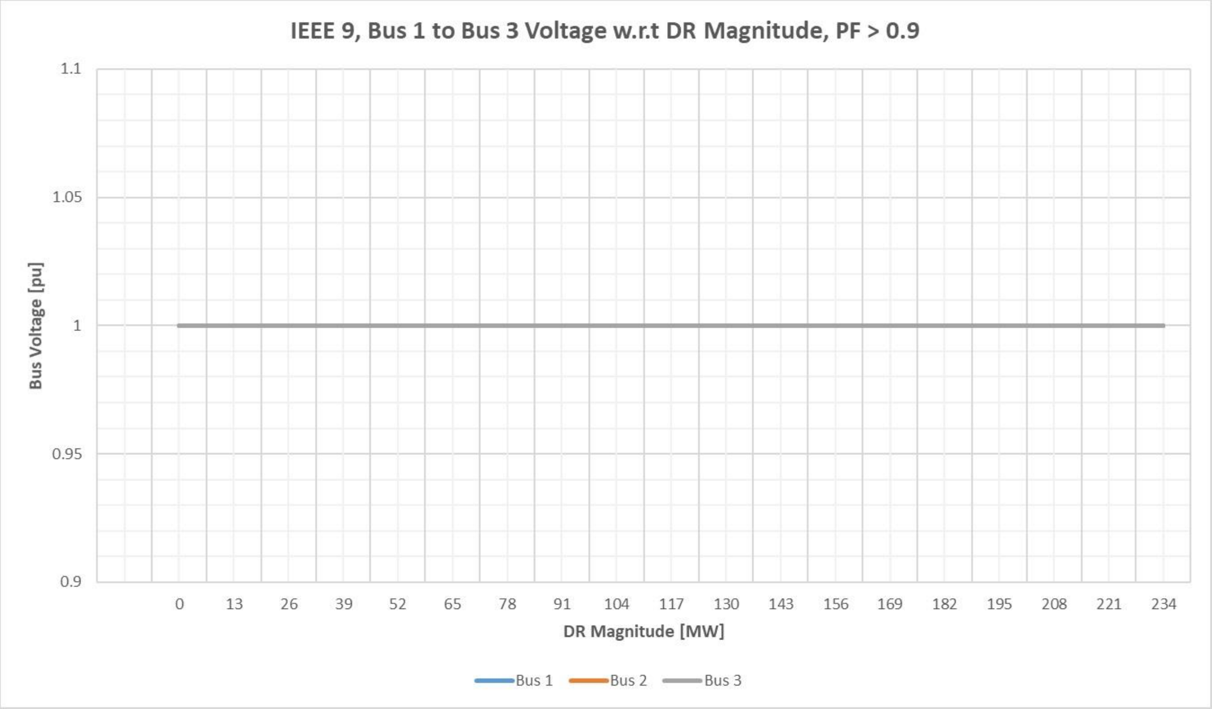

Figure 14: IEEE 9 Bus 1 to 3 Voltage w.r.t DR at PF>0.9

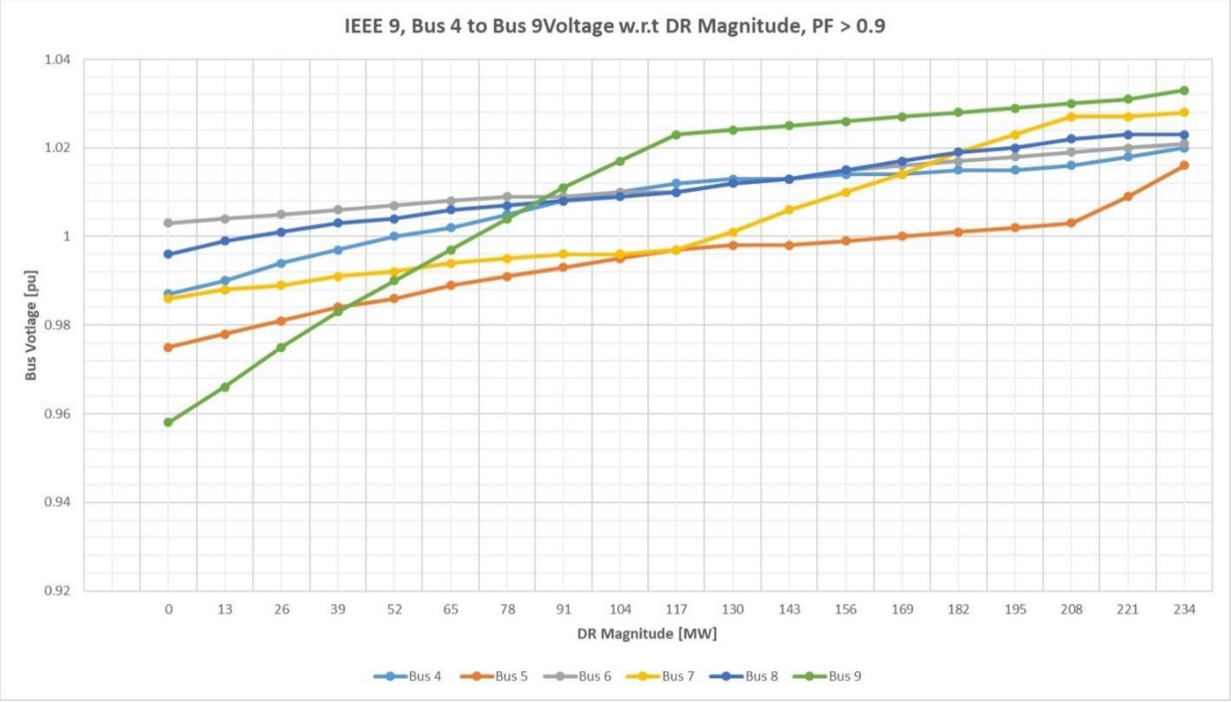

Figure 15: IEEE 9 Bus 4 to 9 Voltage w.r.t DR at PF>0.9

4.4.2 Results of Load Flow when Load Power Factor is between the range: 0.5<PF<0.6

The following table lists the Bus Voltages, when DR is applied on Load with Power Factor greater than 0.5PF but less than 0.6PF.

Table 10: Bus Voltage for IEEE 9 w.r.t DR at 0.5<PF<0.6

DR	**Bus 1**	**Bus 2**	**Bus 3**	**Bus 4**	**Bus 5**	**Bus 6**	**Bus 7**	**Bus 8**	**Bus 9**
[MW]	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**
0	1	1	1	0.92	0.922	0.983	0.95	0.952	0.78
13	1	1	1	0.934	0.934	0.987	0.958	0.961	0.816
26	1	1	1	0.946	0.944	0.991	0.964	0.969	0.849
39	1	1	1	0.957	0.953	0.995	0.97	0.977	0.878
52	1	1	1	0.968	0.961	0.998	0.975	0.983	0.905
65	1	1	1	0.977	0.969	1	0.98	0.989	0.93
78	1	1	1	0.986	0.976	1.003	0.985	0.995	0.953
91	1	1	1	0.994	0.982	1.005	0.988	0.999	0.975
104	1	1	1	1.002	0.988	1.007	0.992	1.004	0.995
117	1	1	1	1.009	0.994	1.009	0.995	1.008	1.015
130	1	1	1	1	0.978	0.983	0.918	0.975	0.997
143	1	1	1	1.002	0.982	0.989	0.937	0.982	1.001
156	1	1	1	1.004	0.985	0.995	0.954	0.989	1.005
169	1	1	1	1.006	0.989	1.001	0.971	0.997	1.009
182	1	1	1	1.008	0.992	1.006	0.987	1.004	1.013
195	1	1	1	1.01	0.995	1.011	1.003	1.01	1.016
208	1	1	1	1.012	0.999	1.016	1.018	1.017	1.02
221	1	1	1	0.982	0.913	0.996	1.004	1.007	0.997
234	1	1	1	0.99	0.938	1	1.007	1.01	1.003

The following table lists the total Generation, Losses and Loads for each step of DR applied at above mentioned PF.

Table 11: Power Generation vs Load and Loss at 0.5<PF<0.6

DR	**Generation**		**Losses**		**Load**	
[MW]	**[MW]**	**[MVAR]**	**[MW]**	**[MVAR]**	**[MW]**	**[MVAR]**
0	325.9	257.2	11	107	315	265
13	310.4	209	8.4	83	302	244.2
26	295.4	166.8	6.4	54.6	289	223.4
39	280.9	129.1	4.9	50.4	276	202.6
52	266.7	94.8	3.7	39.5	263	181.8
65	252.8	63.4	2.8	31.2	250	161
78	239.2	34.4	2.2	25.3	237	140.2
91	225.8	7.5	1.8	21.3	224	119.4

104	212.6	-17.6	1.6	19	211	98.6
117	199.6	-41.1	1.6	18.2	198	77.8
130	187.5	74	2.5	26.2	185	177.2
143	174.1	47.4	2.1	21.5	172	157.1
156	160.8	22.4	1.8	18.2	159	137
169	147.4	-3.4	1.4	14.1	146	117
182	134.2	-27.9	1.2	11.4	133	96.9
195	121	-51.1	1.1	9.9	120	76.8
208	108	-73	1	9.5	107	56.7
221	96.3	28.7	2.3	15.5	94	144
234	82.5	2.1	1.5	10.9	81	124.2

Graphs of Bus Voltages are as follows. Bus 1 to 3 are the Buses with Generators attached to them.

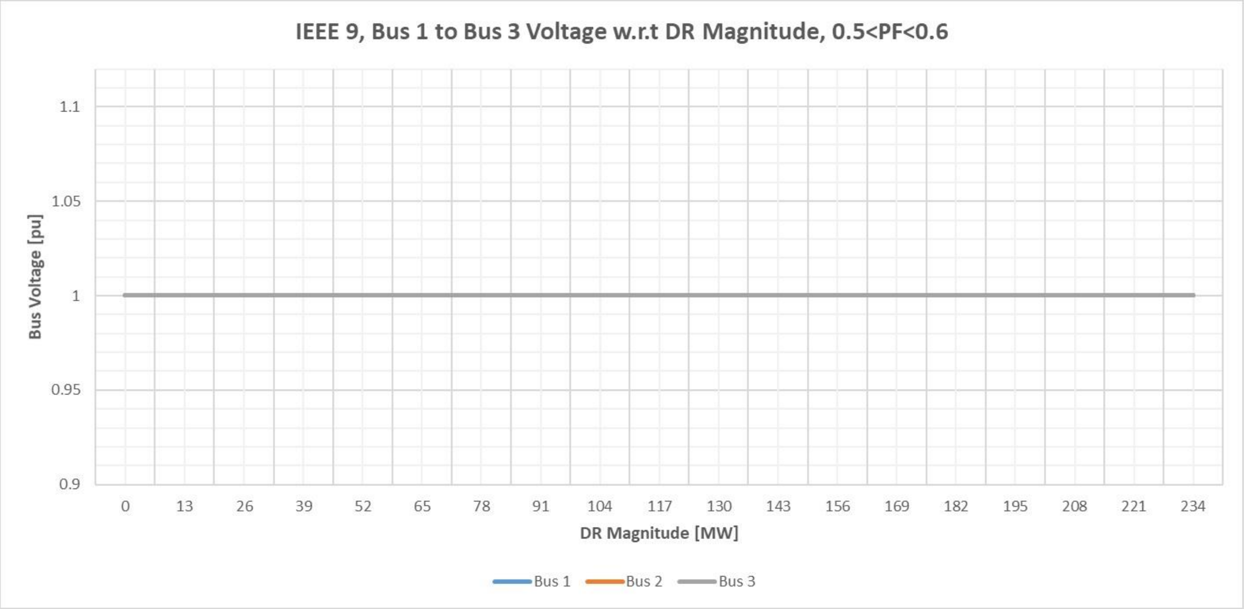

Figure 16: IEEE 9 Bus 1 to 3 Voltage w.r.t DR at 0.5<PF<0.6

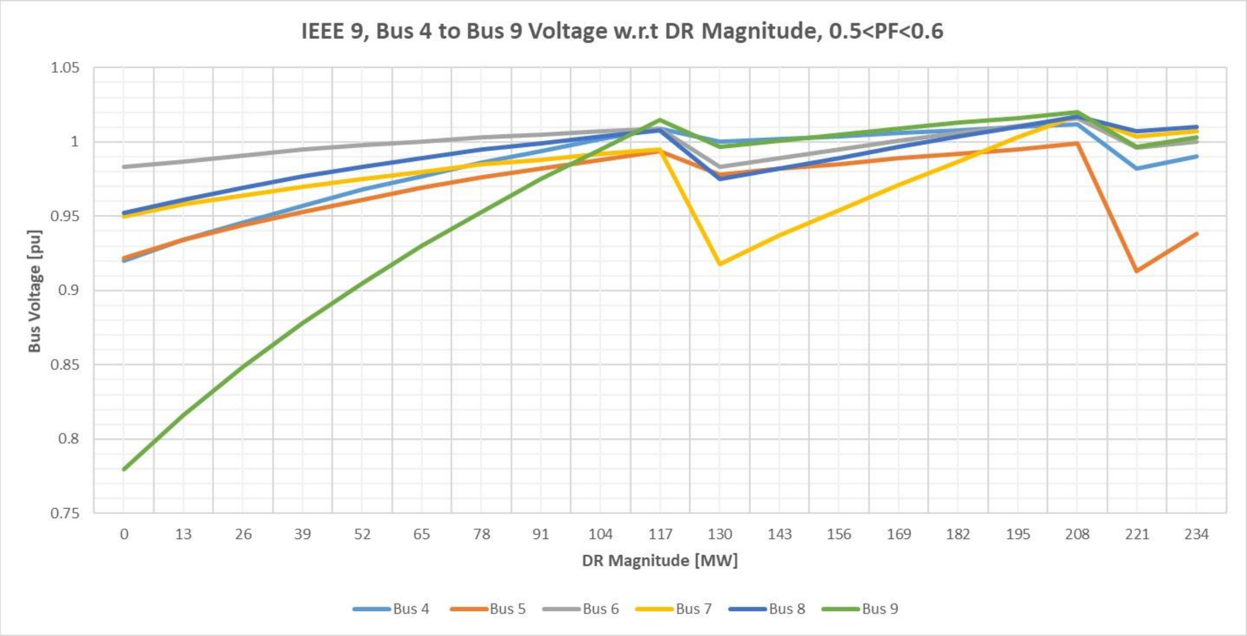

Figure 17: IEEE 9 Bus system, Bus 4 to Bus 9 Voltage w.r.t DR at 0.5<PF<0.6

4.4.3 Comparison of Bus Voltages at different DR Power Factor

The following table and graph represent a comparison between Bus Voltages when DR Load is different for Bus 9 and is intended for a representation of general trend.

Table 12: Bus 9 Voltage at Different PF vs DR

DR	Bus 9 (0.9PF)	Bus 9 (0.5PF)
[MW]	[pu]	[pu]
0	0.958	0.78
13	0.966	0.816
26	0.975	0.849
39	0.983	0.878
52	0.99	0.905
65	0.997	0.93
78	1.004	0.953
91	1.011	0.975
104	1.017	0.995
117	1.023	1.015
130	1.024	0.997
143	1.025	1.001
156	1.026	1.005
169	1.027	1.009
182	1.028	1.013
195	1.029	1.016
208	1.03	1.02
221	1.031	0.997
234	1.033	1.003

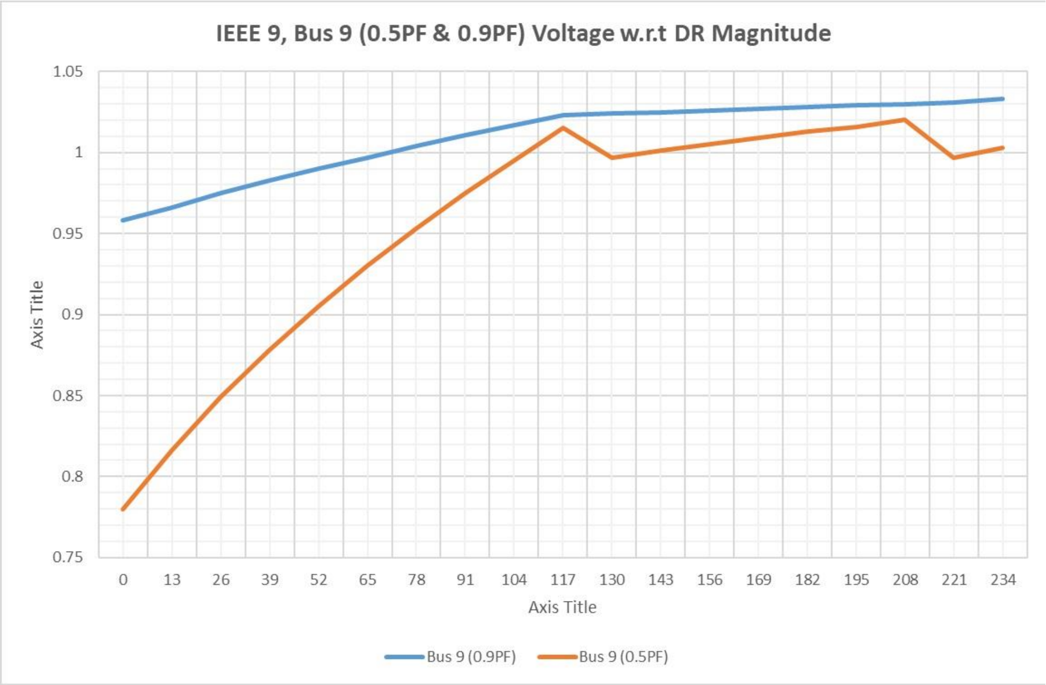

Figure 18: IEEE 9 Bus System, Bus 9 Voltage at Different PF

4.5 Results for IEEE 39 Bus System

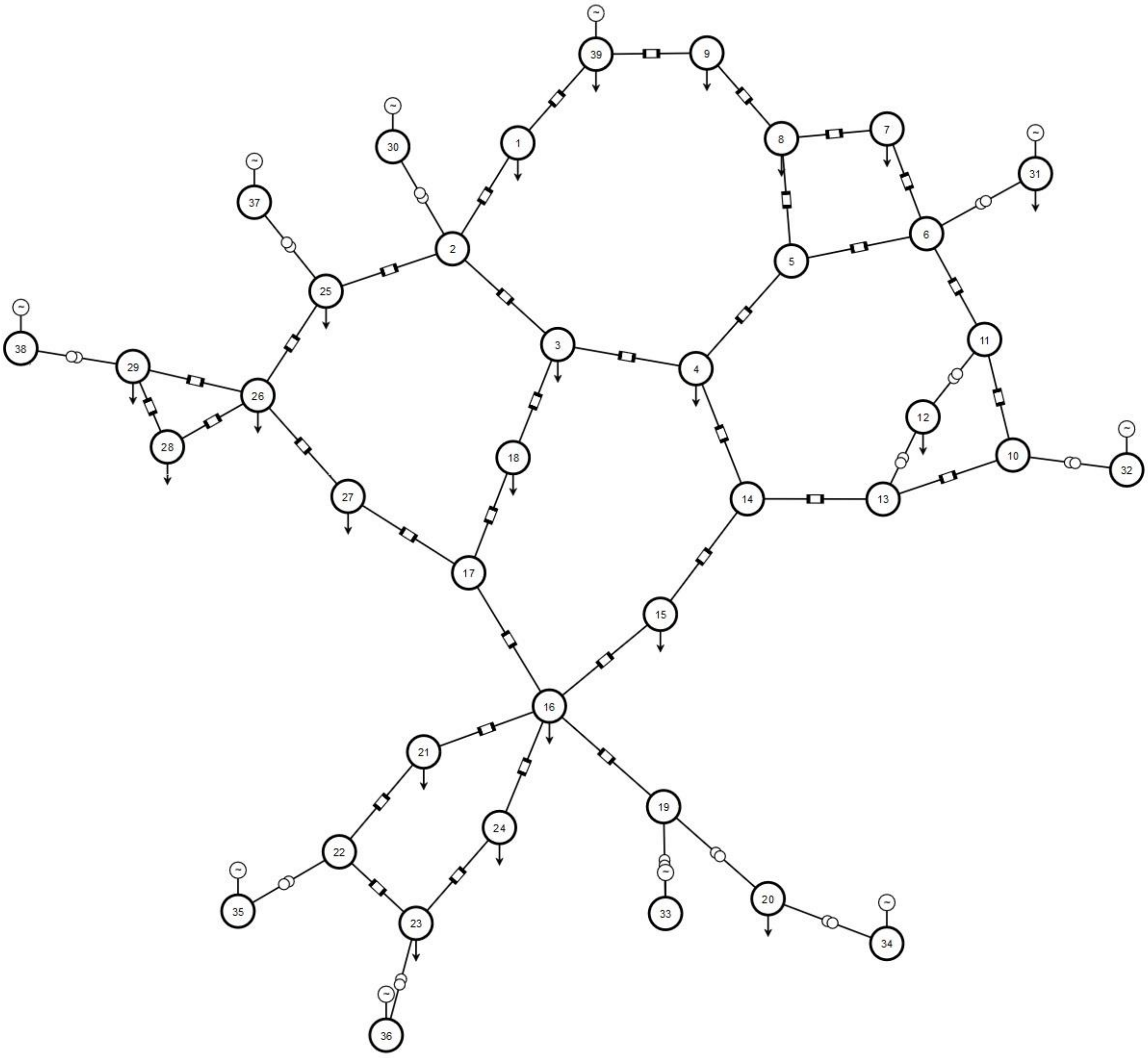

Figure 19: IEEE 39 Bus System

- Load: 6254MW
- Base Voltage: 345kV
- DR Step: 60MW
- Maximum DR Applied (of total load): 5400MW (87%)

The following table provides the sequence of Generation outage and DR active power balancing. For the purpose of decreasing complexity, only those steps are listed that were used to perform Load Flow.

Table 13: Sequence of Generation Outage and DR Active Power Balancing

Step No.	DR	Gen Bus	Gen	Load Bus	Load
	[MW]		[MW]		[MW]
1	0	39	1000	20	680
5	240	39	760	20	440
10	540	39	460	20	140
12	660	39	340	20	20
13	720	39	280	8	462
17	960	39	40	8	222
18	1020	38	770	8	162
20	1140	38	650	8	42
21	1200	38	590	39	1044
25	1440	38	350	39	804
30	1740	38	50	39	504
31	1800	36	500	39	444
38	2220	36	80	39	24
39	2280	36	20	4	440
40	2340	35	590	4	380
46	2700	35	230	4	20
47	2760	35	170	29	224
49	2880	35	50	29	104
50	2940	34	448	29	44
51	3000	34	388	27	221
54	3180	34	208	27	41
55	3240	34	148	21	214
58	3420	33	572	21	34
59	3480	33	512	23	188
62	3660	33	332	23	8
63	3720	33	272	15	260
67	3960	33	32	15	20
68	4020	32	590	16	269
70	4140	32	470	16	149
72	4260	32	350	16	29
73	4320	32	290	3	262
77	4560	32	50	3	22
78	4620	31	618	7	174
80	4740	31	498	7	54
81	4800	31	438	18	98
82	4860	31	378	18	38
83	4920	31	318	25	164
85	5040	31	198	25	44
86	5100	31	138	26	79
87	5160	31	78	26	19
89	5280	30	190	28	86
90	5340	30	130	28	26

91	5400	30	70	1	37.6

4.5.1 Results of Load Flow when Load Power Factor is > 0.9PF

The following tables lists the Bus Voltages, when DR is applied on Load with Power Factor minimum of 0.9PF.

- For Bus 1 to 10

Table 14: IEEE 39 Bus System, Bus 1 to 10 Voltage w.r.t DR at PF>0.9

DR	**Bus 1**	**Bus 2**	**Bus 3**	**Bus 4**	**Bus 5**	**Bus 6**	**Bus 7**	**Bus 8**	**Bus 9**	**Bus 10**
[MW]	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**
0	1.039	1.048	1.031	1.004	1.006	1.008	0.998	0.998	1.038	1.018
240	1.035	1.046	1.028	1.001	1.003	1.005	0.995	0.994	1.035	1.015
540	1.026	1.039	1.02	0.993	0.995	0.997	0.986	0.985	1.028	1.009
660	1.022	1.036	1.015	0.988	0.99	0.993	0.981	0.98	1.024	1.006
720	1.02	1.035	1.016	0.99	0.992	0.995	0.983	0.982	1.024	1.007
960	1.014	1.033	1.016	0.993	0.997	1	0.99	0.99	1.02	1.01
1020	1.016	1.035	1.018	0.995	1	1.003	0.994	0.994	1.021	1.012
1140	1.018	1.038	1.021	1	1.006	1.008	1.001	1.002	1.023	1.016
1200	1.021	1.04	1.023	1.001	1.008	1.01	1.003	1.004	1.025	1.017
1440	1.031	1.046	1.027	1.005	1.013	1.015	1.01	1.012	1.034	1.02
1740	1.038	1.049	1.028	1.007	1.016	1.018	1.014	1.016	1.041	1.022
1800	1.039	1.05	1.029	1.008	1.017	1.019	1.016	1.018	1.042	1.023
2220	1.044	1.054	1.034	1.012	1.022	1.023	1.021	1.024	1.048	1.026
2280	1.044	1.055	1.036	1.016	1.024	1.025	1.023	1.025	1.049	1.027
2340	1.044	1.055	1.037	1.019	1.026	1.027	1.024	1.027	1.05	1.029
2700	1.045	1.058	1.043	1.035	1.035	1.035	1.033	1.035	1.053	1.036
2760	1.045	1.059	1.044	1.035	1.036	1.036	1.033	1.036	1.053	1.036
2880	1.045	1.059	1.045	1.036	1.036	1.036	1.033	1.036	1.053	1.036
2940	1.046	1.06	1.046	1.037	1.037	1.037	1.034	1.037	1.054	1.037
3000	1.046	1.06	1.048	1.038	1.038	1.038	1.035	1.037	1.054	1.037
3180	1.047	1.063	1.052	1.041	1.04	1.04	1.037	1.039	1.055	1.04
3240	1.047	1.063	1.053	1.042	1.041	1.04	1.038	1.04	1.055	1.04
3420	1.048	1.065	1.057	1.046	1.043	1.043	1.04	1.042	1.056	1.043
3480	1.048	1.065	1.058	1.046	1.043	1.043	1.04	1.043	1.056	1.043
3660	1.048	1.066	1.06	1.048	1.045	1.044	1.041	1.044	1.057	1.045
3720	1.048	1.067	1.061	1.05	1.046	1.045	1.042	1.045	1.057	1.046
3960	1.049	1.069	1.065	1.055	1.05	1.049	1.046	1.048	1.059	1.05
4020	1.049	1.069	1.067	1.057	1.051	1.051	1.047	1.05	1.059	1.052
4140	1.05	1.07	1.069	1.061	1.054	1.053	1.05	1.052	1.06	1.055
4260	1.05	1.071	1.072	1.063	1.056	1.055	1.052	1.054	1.061	1.057
4320	1.05	1.072	1.073	1.065	1.057	1.056	1.053	1.055	1.062	1.058
4560	1.051	1.073	1.076	1.067	1.059	1.058	1.055	1.057	1.063	1.059
4620	1.051	1.074	1.077	1.069	1.062	1.061	1.059	1.061	1.064	1.061

4740	1.051	1.074	1.079	1.073	1.068	1.066	1.067	1.067	1.067	1.064
4800	1.051	1.075	1.08	1.074	1.069	1.067	1.068	1.068	1.067	1.065
4860	1.051	1.076	1.082	1.075	1.069	1.068	1.068	1.069	1.068	1.066
4920	1.051	1.076	1.082	1.076	1.07	1.068	1.069	1.069	1.068	1.066
5040	1.051	1.075	1.081	1.076	1.07	1.068	1.069	1.069	1.068	1.066
5100	1.051	1.075	1.082	1.076	1.07	1.068	1.069	1.069	1.068	1.066
5160	1.051	1.075	1.082	1.076	1.07	1.068	1.068	1.069	1.068	1.066
5280	1.05	1.074	1.081	1.076	1.069	1.068	1.068	1.069	1.068	1.066
5340	1.05	1.074	1.082	1.076	1.069	1.068	1.068	1.069	1.068	1.066
5400	1.055	1.075	1.082	1.076	1.07	1.068	1.068	1.069	1.068	1.066

- For Bus 11 to 20

Table 15: IEEE 39 Bus System, Bus 11 to 20 Voltage w.r.t DR at PF>0.9

DR	**Bus 11**	**Bus 12**	**Bus 13**	**Bus 14**	**Bus 15**	**Bus 16**	**Bus 17**	**Bus 18**	**Bus 19**	**Bus 20**
[MW]	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**
0	1.013	1.001	1.015	1.012	1.016	1.033	1.034	1.032	1.05	0.991
240	1.011	0.998	1.012	1.009	1.012	1.029	1.031	1.028	1.05	0.995
540	1.004	0.991	1.006	1.001	1.003	1.02	1.022	1.019	1.045	0.997
660	1	0.987	1.002	0.997	0.998	1.015	1.017	1.014	1.042	0.996
720	1.001	0.988	1.003	0.998	0.998	1.015	1.017	1.015	1.042	0.996
960	1.005	0.992	1.006	1.001	1	1.016	1.018	1.015	1.043	0.996
1020	1.008	0.994	1.008	1.003	1.001	1.017	1.019	1.017	1.043	0.997
1140	1.012	0.998	1.012	1.006	1.004	1.019	1.021	1.019	1.044	0.997
1200	1.013	1	1.013	1.008	1.005	1.019	1.022	1.02	1.044	0.997
1440	1.017	1.003	1.016	1.011	1.007	1.02	1.023	1.023	1.044	0.997
1740	1.019	1.005	1.018	1.012	1.006	1.019	1.02	1.021	1.044	0.997
1800	1.02	1.006	1.019	1.013	1.008	1.02	1.021	1.023	1.044	0.997
2220	1.024	1.01	1.022	1.017	1.014	1.027	1.028	1.029	1.047	0.999
2280	1.026	1.011	1.024	1.019	1.015	1.028	1.029	1.031	1.047	0.999
2340	1.027	1.013	1.025	1.021	1.016	1.029	1.031	1.032	1.048	0.999
2700	1.034	1.021	1.033	1.031	1.02	1.032	1.034	1.036	1.049	1
2760	1.035	1.021	1.033	1.031	1.021	1.032	1.036	1.037	1.049	1
2880	1.035	1.021	1.033	1.031	1.021	1.032	1.037	1.039	1.049	1
2940	1.036	1.022	1.034	1.032	1.023	1.035	1.039	1.04	1.051	1.002
3000	1.036	1.023	1.035	1.034	1.025	1.037	1.043	1.043	1.053	1.003
3180	1.039	1.025	1.037	1.037	1.031	1.044	1.051	1.05	1.058	1.008
3240	1.039	1.026	1.038	1.038	1.033	1.048	1.054	1.052	1.06	1.009
3420	1.042	1.029	1.041	1.042	1.041	1.056	1.06	1.058	1.065	1.012
3480	1.042	1.029	1.042	1.043	1.042	1.058	1.062	1.059	1.066	1.012
3660	1.043	1.031	1.043	1.045	1.046	1.063	1.065	1.062	1.069	1.014
3720	1.045	1.032	1.045	1.048	1.061	1.065	1.067	1.063	1.07	1.014
3960	1.049	1.037	1.05	1.056	1.068	1.074	1.074	1.069	1.074	1.016
4020	1.051	1.039	1.052	1.058	1.071	1.076	1.076	1.071	1.075	1.017

4140	1.053	1.042	1.056	1.062	1.075	1.08	1.079	1.074	1.076	1.017
4260	1.056	1.045	1.058	1.065	1.078	1.083	1.082	1.077	1.077	1.018
4320	1.056	1.045	1.059	1.066	1.079	1.083	1.082	1.077	1.077	1.018
4560	1.058	1.047	1.061	1.069	1.081	1.085	1.084	1.08	1.078	1.018
4620	1.06	1.049	1.063	1.07	1.082	1.086	1.085	1.08	1.078	1.019
4740	1.064	1.053	1.066	1.073	1.084	1.087	1.086	1.082	1.078	1.019
4800	1.065	1.054	1.067	1.075	1.085	1.088	1.088	1.084	1.079	1.019
4860	1.066	1.055	1.068	1.076	1.086	1.089	1.089	1.087	1.079	1.019
4920	1.066	1.055	1.068	1.076	1.086	1.089	1.09	1.087	1.079	1.019
5040	1.066	1.055	1.068	1.076	1.087	1.089	1.09	1.087	1.079	1.019
5100	1.066	1.055	1.068	1.076	1.087	1.09	1.091	1.087	1.08	1.019
5160	1.066	1.055	1.068	1.076	1.087	1.09	1.091	1.088	1.08	1.019
5280	1.066	1.055	1.068	1.076	1.088	1.091	1.092	1.088	1.08	1.02
5340	1.066	1.055	1.068	1.077	1.088	1.091	1.092	1.089	1.08	1.02
5400	1.066	1.055	1.068	1.077	1.088	1.091	1.093	1.089	1.08	1.02

- For Bus 21 to 29

Table 16: IEEE 39 Bus System, Bus 21 to 29 Voltage w.r.t DR at PF>0.9

DR	**Bus 21**	**Bus 22**	**Bus 23**	**Bus 24**	**Bus 25**	**Bus 26**	**Bus 27**	**Bus 28**	**Bus 29**
[MW]	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**
0	1.032	1.05	1.045	1.038	1.058	1.053	1.038	1.05	1.05
240	1.03	1.049	1.044	1.035	1.057	1.051	1.036	1.05	1.05
540	1.023	1.045	1.04	1.027	1.055	1.047	1.03	1.048	1.048
660	1.02	1.043	1.038	1.022	1.053	1.045	1.026	1.046	1.047
720	1.02	1.044	1.038	1.022	1.053	1.045	1.027	1.046	1.047
960	1.02	1.044	1.039	1.023	1.052	1.045	1.027	1.046	1.047
1020	1.021	1.044	1.039	1.024	1.053	1.047	1.028	1.049	1.049
1140	1.023	1.045	1.04	1.025	1.053	1.049	1.031	1.052	1.052
1200	1.023	1.045	1.04	1.026	1.053	1.05	1.031	1.053	1.053
1440	1.024	1.046	1.04	1.027	1.052	1.049	1.031	1.054	1.054
1740	1.022	1.045	1.04	1.025	1.046	1.039	1.023	1.045	1.048
1800	1.024	1.046	1.041	1.027	1.047	1.04	1.024	1.046	1.048
2220	1.031	1.051	1.047	1.034	1.046	1.042	1.029	1.047	1.049
2280	1.032	1.052	1.047	1.035	1.046	1.043	1.03	1.047	1.049
2340	1.033	1.052	1.048	1.036	1.047	1.043	1.031	1.048	1.05
2700	1.035	1.054	1.049	1.039	1.047	1.044	1.034	1.048	1.05
2760	1.036	1.054	1.05	1.039	1.049	1.048	1.036	1.052	1.053
2880	1.035	1.053	1.049	1.039	1.052	1.053	1.04	1.057	1.058
2940	1.037	1.054	1.05	1.041	1.053	1.056	1.043	1.06	1.061
3000	1.039	1.055	1.051	1.044	1.055	1.06	1.048	1.062	1.062
3180	1.044	1.058	1.054	1.05	1.059	1.069	1.062	1.067	1.065
3240	1.048	1.06	1.056	1.053	1.06	1.07	1.064	1.068	1.066
3420	1.062	1.066	1.061	1.061	1.062	1.074	1.069	1.069	1.067
3480	1.064	1.068	1.064	1.064	1.062	1.074	1.07	1.07	1.067

3660	1.069	1.073	1.072	1.069	1.063	1.076	1.072	1.071	1.068
3720	1.07	1.074	1.073	1.071	1.063	1.077	1.074	1.071	1.068
3960	1.077	1.077	1.076	1.079	1.065	1.08	1.079	1.073	1.069
4020	1.078	1.078	1.077	1.081	1.066	1.081	1.08	1.073	1.069
4140	1.08	1.079	1.078	1.084	1.067	1.083	1.083	1.074	1.07
4260	1.083	1.08	1.079	1.087	1.068	1.085	1.085	1.075	1.071
4320	1.083	1.081	1.08	1.088	1.069	1.085	1.085	1.075	1.071
4560	1.084	1.081	1.08	1.089	1.069	1.086	1.086	1.076	1.071
4620	1.084	1.081	1.08	1.089	1.07	1.086	1.087	1.076	1.071
4740	1.085	1.082	1.081	1.09	1.07	1.087	1.088	1.076	1.071
4800	1.086	1.082	1.081	1.092	1.071	1.088	1.089	1.077	1.072
4860	1.087	1.083	1.082	1.092	1.071	1.089	1.09	1.077	1.072
4920	1.087	1.083	1.082	1.093	1.074	1.09	1.091	1.078	1.072
5040	1.087	1.083	1.082	1.093	1.079	1.091	1.092	1.078	1.073
5100	1.087	1.083	1.082	1.093	1.08	1.094	1.094	1.08	1.074
5160	1.088	1.083	1.082	1.094	1.082	1.096	1.095	1.081	1.075
5280	1.088	1.083	1.082	1.094	1.084	1.1	1.098	1.088	1.078
5340	1.088	1.083	1.083	1.094	1.085	1.102	1.099	1.091	1.08
5400	1.088	1.083	1.083	1.094	1.086	1.102	1.099	1.091	1.08

- For Bus 30 to 39 (Generator Buses)

Table 17: IEEE 39 Bus System, Bus 30 to 39 Voltage w.r.t DR at PF>0.9

DR [MW]	**Bus 30 [pu]**	**Bus 31 [pu]**	**Bus 32 [pu]**	**Bus 33 [pu]**	**Bus 34 [pu]**	**Bus 35 [pu]**	**Bus 36 [pu]**	**Bus 37 [pu]**	**Bus 38 [pu]**	**Bus 39 [pu]**
0	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
240	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
540	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
660	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
720	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
960	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
1020	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
1140	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
1200	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
1440	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
1740	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
1800	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
2220	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
2280	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
2340	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
2700	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
2760	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
2880	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
2940	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
3000	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03

3180	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
3240	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
3420	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
3480	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
3660	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
3720	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
3960	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
4020	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
4140	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
4260	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
4320	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
4560	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
4620	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
4740	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
4800	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
4860	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
4920	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
5040	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
5100	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
5160	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
5280	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
5340	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
5400	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03

The following table lists the total Generation, Losses and Loads for each step of DR applied at above mentioned PF.

Table 18: Power Generation vs Load and Loss

DR	**Generation**		**Losses**		**Load**	
[MW]	**[MW]**	**[MVAR]**	**[MW]**	**[MVAR]**	**[MW]**	**[MVAR]**
0	6297.9	1274.9	43.64	1000.59	6254.2	1387.1
240	6067.9	1364	53.71	1121.8	6014	1350.7
540	5790.7	1635.4	76.5	1426.5	5714	1305.3
660	5683.3	1797.7	89.04	1600	5594.2	1287.1
720	5625	1803.6	90.78	1626.2	5534	1267
960	5394	1861.8	99.81	1765.7	5294	1185.8
1020	5329	1791.6	95.5	1719.2	5234	1165
1140	5202.8	1674.3	88.53	1648.03	5114.2	1124.7
1200	5137.5	1589.1	83.22	1579	5054.2	1111.1
1440	4883.3	1338.9	69.04	1389	4814.2	1056.8
1740	4581.5	1226	67.25	1341.4	4514.2	988.8
1800	4518.4	1148.5	64.2	1279.7	4454.2	975.2
2220	4088.2	825.8	54	1060	4034.2	880.1
2280	4028.1	795.2	53.84	1053.1	3974.2	858

2340	3967.9	755.5	53.68	1037.2	3914.2	835.9
2700	3611.3	608.3	57.11	1029	3554.2	703.5
2760	3548.9	571.7	54.6	1000.5	3494.2	697.9
2880	3425.6	521.9	51.3	965.6	3374.2	686.5
2940	3361.2	453.1	47	905.5	3314.2	680.8
3000	3297.9	384.9	43.67	857	3254.2	664.7
3180	3110.4	217.9	36.15	747.7	3074.2	616.3
3240	3048.3	158.4	34.02	715.6	3014.2	591.1
3420	2863.1	-0.1	28.91	639.8	2834.2	515.6
3480	2801.4	-49.1	27.19	612.6	2774.2	495.4
3660	2617.7	-172.6	23.5	554.9	2594.2	433.7
3720	2557	-214.7	22.8	543.6	2534.2	405
3960	2316.5	-350	22.3	531.2	2294.2	290.3
4020	2254.5	-399	20.3	490.3	2234.2	284.2
4140	2131.1	-485.2	16.9	420	2114.2	275.5
4260	2008.3	-556.1	14.1	364.1	1994.2	260.8
4320	1947.5	-577	13.3	344.5	1934.2	260.4
4560	1705.4	-628.5	11.1	297.3	1694.2	258.6
4620	1645.2	-672.7	10.98	276.3	1634.2	237.1
4740	1525	-753	10.79	242.2	1514.2	194
4800	1464.4	-787.6	10.13	220.7	1454.2	182.6
4860	1403.8	-818.4	9.6	202.9	1394.2	171.2
4920	1344.2	-840	9.94	194.88	1334.2	158.4
5040	1226	-870.6	11.73	190.57	1214.2	133.2
5100	1166	-886.3	11.8	183.5	1154.2	125.9
5160	1106.4	-897.7	12.15	180.7	1094.2	118.5
5280	986.7	-932.1	12.47	164.95	974.2	102.6
5340	927.3	-949.6	13.05	157	914.2	94
5400	867	-983.4	12.79	151.6	854.2	67.3

Graphs of Bus Voltages are as follows.

- Bus 1 (Representative of the trend)

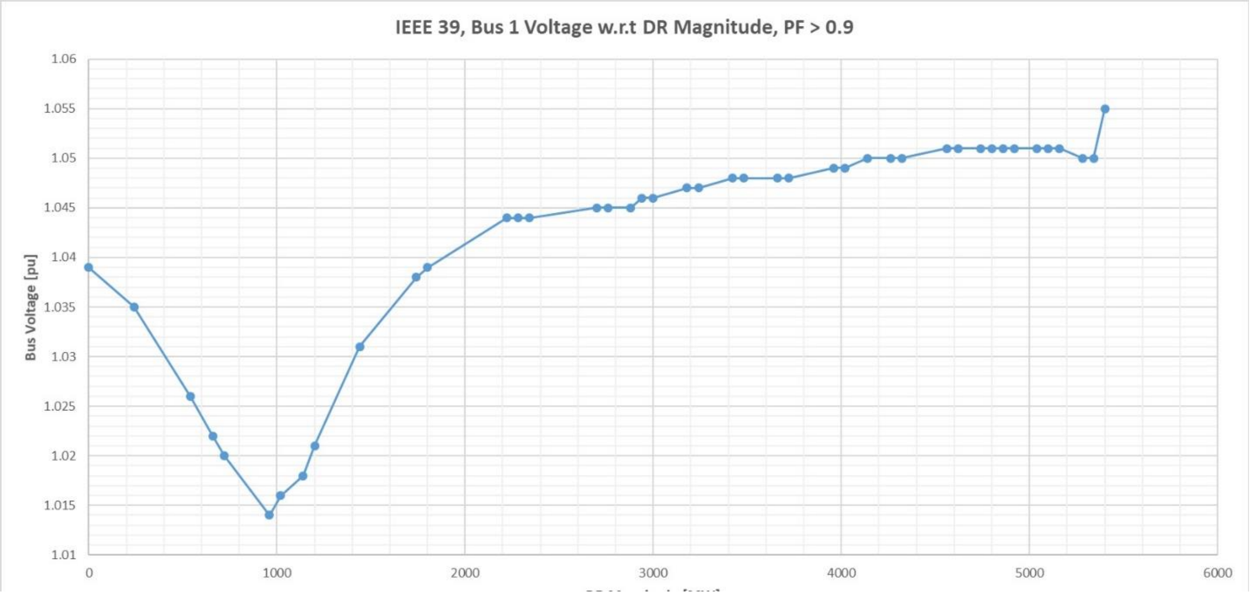

Figure 20: IEEE 39 Bus System, Bus 1 Voltage w.r.t DR at PF > 0.9

- Bus 1 to Bus 29

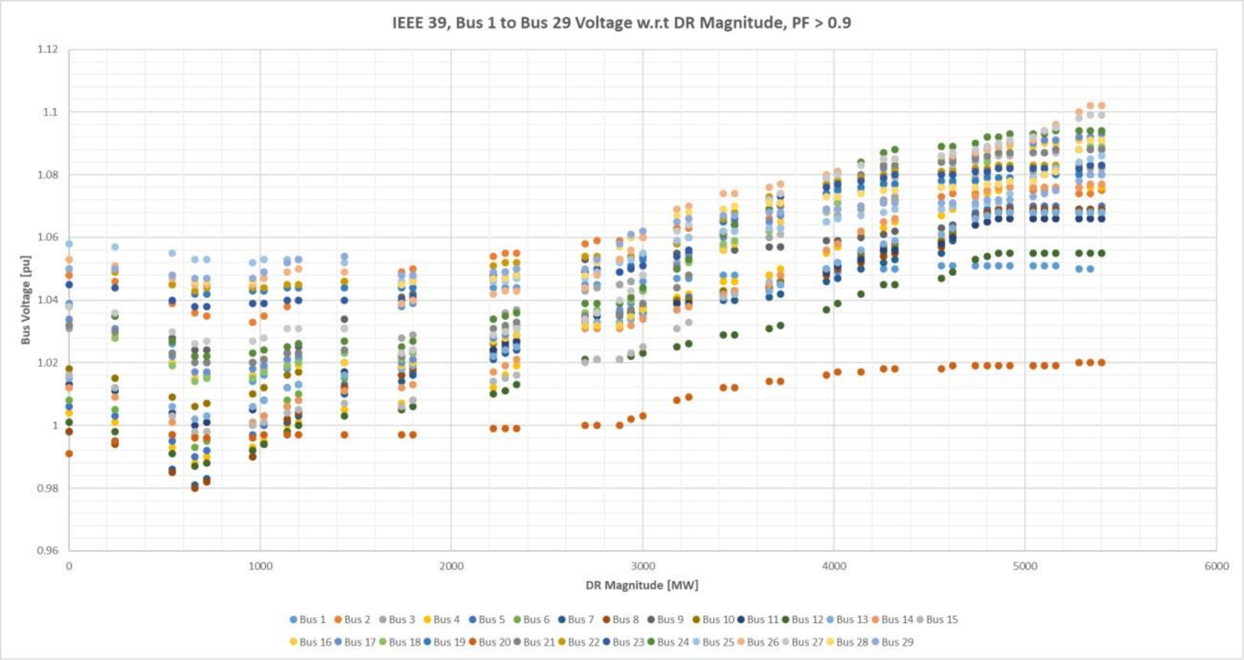

Figure 21: IEEE 39 Bus System, Bus 01 to 29 Voltage w.r.t DR at PF>0.9

- Bus 30 to Bus 39

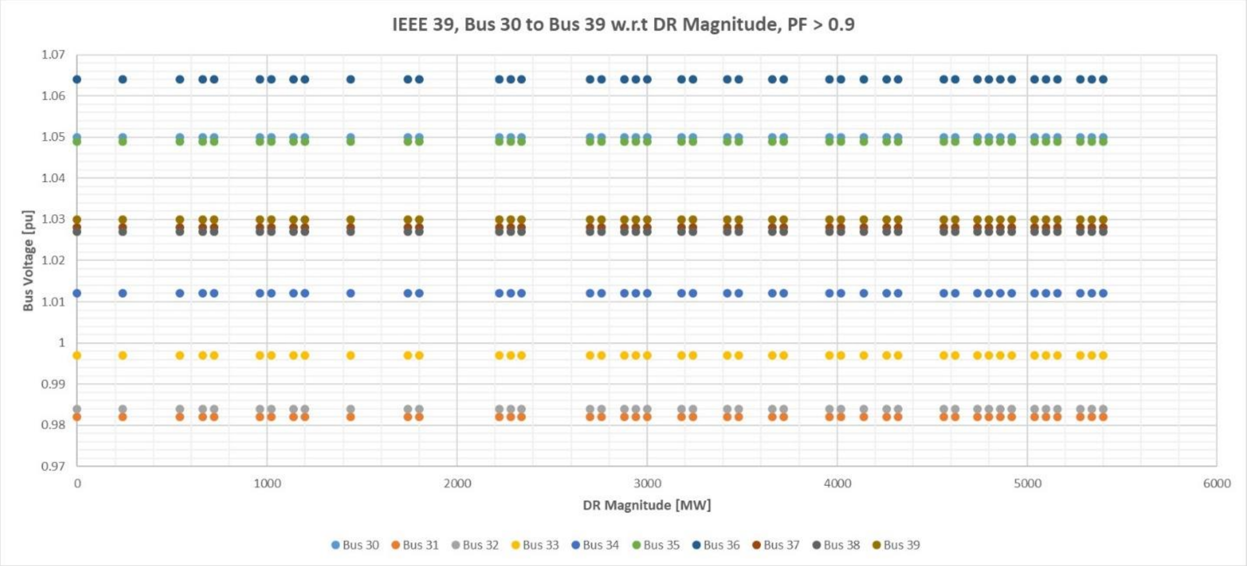

Figure 22: IEEE 39 Bus system, Bus 30 to 39 Voltage w.r.t DR at PF>0.9

4.5.2 Results of Load Flow when Load Power Factor is between the range: 0.5<PF<0.6

The following table lists the Bus Voltages, when DR is applied on Load with Power Factor greater than 0.5PF but less than 0.6PF.

- For Bus 1 to 10

Table 19: IEEE 39 Bus System, Bus 1 to 10 Voltage w.r.t DR at 0.5<PF<0.6

DR [MW]	Bus 1 [pu]	Bus 2 [pu]	Bus 3 [pu]	Bus 4 [pu]	Bus 5 [pu]	Bus 6 [pu]	Bus 7 [pu]	Bus 8 [pu]	Bus 9 [pu]	Bus 10 [pu]
0	1.038	1.045	1.024	0.998	1.002	1.004	0.994	0.994	1.037	1.013
240	1.034	1.043	1.023	0.997	1	1.002	0.992	0.991	1.034	1.012
540	1.026	1.039	1.018	0.992	0.994	0.996	0.985	0.984	1.028	1.008
660	1.022	1.036	1.015	0.988	0.99	0.993	0.981	0.98	1.024	1.006
720	1.015	1.026	0.994	0.945	0.929	0.935	0.9	0.889	0.985	0.968
960	1.012	1.029	1.006	0.973	0.969	0.973	0.954	0.949	1.002	0.993
1020	1.014	1.032	1.011	0.981	0.98	0.984	0.968	0.965	1.008	1
1140	1.018	1.037	1.019	0.996	1.001	1.003	0.995	0.995	1.02	1.013
1200	1.021	1.039	1.021	0.997	1.003	1.005	0.997	0.997	1.022	1.014
1440	1.03	1.045	1.025	1.002	1.008	1.01	1.003	1.004	1.031	1.017
1740	1.038	1.049	1.026	1.003	1.011	1.013	1.008	1.009	1.038	1.019
1800	1.039	1.05	1.027	1.005	1.012	1.015	1.009	1.011	1.039	1.02
2220	1.043	1.053	1.032	1.009	1.017	1.019	1.015	1.017	1.046	1.023
2280	1.038	1.04	1	0.941	0.976	0.982	0.978	0.981	1.031	0.991

2340	1.039	1.043	1.007	0.955	0.984	0.99	0.986	0.988	1.034	0.998
2700	1.045	1.057	1.04	1.029	1.029	1.029	1.025	1.027	1.049	1.031
2760	1.044	1.054	1.037	1.027	1.028	1.028	1.024	1.026	1.049	1.03
2880	1.044	1.056	1.04	1.028	1.029	1.029	1.025	1.027	1.05	1.031
2940	1.045	1.058	1.042	1.03	1.03	1.03	1.026	1.028	1.05	1.032
3000	1.042	1.051	1.032	1.024	1.026	1.027	1.022	1.024	1.049	1.028
3180	1.046	1.059	1.046	1.033	1.032	1.033	1.028	1.03	1.051	1.034
3240	1.045	1.057	1.041	1.029	1.029	1.03	1.025	1.027	1.05	1.031
3420	1.046	1.061	1.05	1.037	1.035	1.035	1.03	1.032	1.052	1.037
3480	1.046	1.06	1.048	1.035	1.033	1.034	1.029	1.031	1.051	1.035
3660	1.047	1.063	1.053	1.039	1.037	1.037	1.032	1.034	1.053	1.039
3720	1.048	1.057	1.042	1.025	1.026	1.027	1.023	1.025	1.049	1.028
3960	1.048	1.065	1.058	1.046	1.041	1.041	1.036	1.038	1.054	1.044
4020	1.046	1.06	1.048	1.037	1.036	1.036	1.031	1.033	1.052	1.038
4140	1.047	1.064	1.056	1.046	1.042	1.042	1.037	1.039	1.055	1.045
4260	1.048	1.067	1.063	1.053	1.047	1.047	1.042	1.043	1.057	1.05
4320	1.042	1.051	1.025	1.035	1.036	1.037	1.032	1.034	1.053	1.041
4560	1.048	1.067	1.064	1.055	1.049	1.048	1.044	1.045	1.058	1.051
4620	1.048	1.065	1.059	1.044	1.033	1.033	1.018	1.024	1.049	1.041
4740	1.049	1.068	1.065	1.057	1.052	1.051	1.047	1.048	1.059	1.053
4800	1.047	1.065	1.058	1.054	1.05	1.049	1.045	1.047	1.058	1.051
4860	1.048	1.068	1.065	1.058	1.053	1.052	1.048	1.049	1.059	1.053
4920	1.044	1.058	1.058	1.055	1.051	1.05	1.046	1.048	1.059	1.052
5040	1.047	1.065	1.63	1.057	1.052	1.052	1.048	1.049	1.059	1.053
5100	1.046	1.062	1.06	1.056	1.051	1.051	1.047	1.048	1.059	1.052
5160	1.046	1.064	1.062	1.057	1.052	1.051	1.047	1.049	1.059	1.053
5280	1.045	1.061	1.061	1.056	1.051	1.05	1.046	1.048	1.059	1.052
5340	1.046	1.062	1.062	1.057	1.052	1.051	1.047	1.048	1.059	1.053
5400	1.043	1.062	1.062	1.057	1.052	1.051	1.047	1.048	1.059	1.053

- For Bus 11 to 20

Table 20: IEEE 39 Bus System, Bus 11 to 20 Voltage w.r.t DR at 0.5<PF<0.6

DR	**Bus 11**	**Bus 12**	**Bus 13**	**Bus 14**	**Bus 15**	**Bus 16**	**Bus 17**	**Bus 18**	**Bus 19**	**Bus 20**
[MW]	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**
0	1.009	0.996	1.01	1.005	1.002	1.016	1.021	1.021	1.007	0.893
240	1.008	0.995	1.009	1.004	1.003	1.018	1.023	1.021	1.023	0.935
540	1.003	0.99	1.005	1	1	1.017	1.02	1.017	1.037	0.978
660	1	0.987	1.002	0.997	0.997	1.014	1.017	1.014	1.041	0.994
720	0.955	0.945	0.964	0.961	0.977	1.001	1.002	0.997	1.036	0.991
960	0.985	0.973	0.989	0.984	0.99	1.009	1.01	1.007	1.039	0.993
1020	0.993	0.981	0.996	0.991	0.994	1.012	1.014	1.011	1.04	0.993
1140	1.008	0.995	1.009	1.003	1.002	1.017	1.02	1.018	1.042	0.994
1200	1.01	0.996	1.01	1.005	1.003	1.018	1.02	1.019	1.042	0.994
1440	1.014	1	1.013	1.008	1.005	1.019	1.022	1.021	1.043	0.995

1740	1.016	1.002	1.015	1.009	1.004	1.017	1.018	1.02	1.042	0.994
1800	1.017	1.003	1.016	1.01	1.006	1.019	1.02	1.021	1.043	0.995
2220	1.02	1.006	1.019	1.014	1.012	1.025	1.027	1.028	1.045	0.996
2280	0.987	0.971	0.983	0.969	0.985	1.007	1.006	1.003	1.038	0.992
2340	0.994	0.978	0.99	0.978	0.99	1.011	1.011	1.008	1.04	0.993
2700	1.03	1.016	1.028	1.026	1.017	1.029	1.032	1.034	1.047	0.997
2760	1.029	1.015	1.027	1.024	1.015	1.027	1.028	1.03	1.046	0.996
2880	1.029	1.016	1.028	1.025	1.016	1.029	1.032	1.034	1.046	0.997
2940	1.03	1.017	1.029	1.027	1.019	1.032	1.036	1.037	1.049	0.999
3000	1.027	1.012	1.025	1.021	1.01	1.021	1.017	1.021	1.046	0.998
3180	1.033	1.019	1.032	1.03	1.025	1.039	1.044	1.043	1.056	1.004
3240	1.029	1.016	1.028	1.025	1.014	1.026	1.034	1.035	1.051	1.002
3420	1.035	1.022	1.035	1.035	1.033	1.049	1.051	1.049	1.061	1.008
3480	1.034	1.021	1.033	1.032	1.029	1.043	1.047	1.046	1.06	1.007
3660	1.037	1.024	1.037	1.038	1.039	1.055	1.056	1.054	1.065	1.01
3720	1.026	1.012	1.024	1.019	0.998	1.034	1.039	1.039	1.058	1.006
3960	1.042	1.03	1.043	1.047	1.057	1.065	1.064	1.06	1.07	1.012
4020	1.036	1.024	1.036	1.037	1.036	1.039	1.044	1.044	1.06	1.007
4140	1.043	1.031	1.044	1.046	1.051	1.055	1.057	1.055	1.066	1.01
4260	1.048	1.037	1.05	1.055	1.065	1.071	1.069	1.066	1.072	1.013
4320	1.039	1.027	1.04	1.042	1.053	1.06	1.051	1.04	1.068	1.011
4560	1.049	1.038	1.052	1.058	1.067	1.072	1.07	1.067	1.072	1.014
4620	1.037	1.027	1.042	1.048	1.062	1.069	1.067	1.062	1.071	1.013
4740	1.051	1.04	1.054	1.059	1.068	1.073	1.071	1.067	1.072	1.014
4800	1.05	1.038	1.052	1.056	1.064	1.068	1.062	1.054	1.071	1.013
4860	1.052	1.041	1.054	1.06	1.068	1.073	1.071	1.066	1.072	1.014
4920	1.051	1.039	1.053	1.058	1.066	1.07	1.066	1.061	1.071	1.013
5040	1.052	1.041	1.054	1.06	1.068	1.073	1.07	1.065	1.072	1.014
5100	1.051	1.04	1.053	1.058	1.066	1.07	1.066	1.062	1.071	1.013
5160	1.052	1.041	1.054	1.06	1.068	1.073	1.07	1.065	1.072	1.014
5280	1.051	1.04	1.053	1.059	1.067	1.072	1.068	1.063	1.072	1.013
5340	1.051	1.04	1.054	1.06	1.069	1.073	1.071	1.065	1.072	1.014
5400	1.051	1.04	1.054	1.059	1.068	1.073	1.071	1.065	1.072	1.014

- For Bus 21 to 29

Table 21: IEEE 39 Bus System, Bus 21 to 29 Voltage w.r.t DR at 0.5<PF<0.6

DR [MW]	**Bus 21 [pu]**	**Bus 22 [pu]**	**Bus 23 [pu]**	**Bus 24 [pu]**	**Bus 25 [pu]**	**Bus 26 [pu]**	**Bus 27 [pu]**	**Bus 28 [pu]**	**Bus 29 [pu]**
0	1.02	1.044	1.039	1.023	1.055	1.046	1.029	1.047	1.048
240	1.022	1.045	1.04	1.025	1.055	1.048	1.03	1.048	1.048
540	1.021	1.044	1.039	1.023	1.054	1.046	1.028	1.047	1.048
660	1.019	1.043	1.038	1.021	1.053	1.045	1.026	1.046	1.047
720	1.01	1.038	1.033	1.009	1.046	1.036	1.015	1.042	1.044
960	1.016	1.041	1.036	1.017	1.049	1.04	1.021	1.044	1.046

1020	1.018	1.042	1.037	1.019	1.05	1.044	1.024	1.047	1.048
1140	1.021	1.044	1.039	1.024	1.052	1.048	1.029	1.051	1.052
1200	1.022	1.045	1.039	1.024	1.053	1.049	1.031	1.053	1.053
1440	1.023	1.045	1.04	1.026	1.052	1.049	1.03	1.053	1.054
1740	1.021	1.044	1.039	1.024	1.046	1.038	1.022	1.045	1.048
1800	1.023	1.046	1.041	1.026	1.046	1.039	1.023	1.045	1.048
2220	1.03	1.051	1.046	1.033	1.045	1.041	1.028	1.047	1.049
2280	1.018	1.044	1.039	1.017	1.035	1.029	1.012	1.04	1.044
2340	1.021	1.046	1.041	1.02	1.037	1.031	1.015	1.041	1.045
2700	1.034	1.053	1.049	1.037	1.046	1.043	1.032	1.048	1.05
2760	1.032	1.052	1.047	1.034	1.043	1.03	1.023	1.02	1.017
2880	1.033	1.052	1.048	1.036	1.049	1.045	1.033	1.043	1.041
2940	1.035	1.053	1.049	1.039	1.051	1.052	1.039	1.054	1.053
3000	1.028	1.049	1.045	1.029	1.043	1.025	0.996	1.04	1.044
3180	1.04	1.056	1.052	1.046	1.056	1.06	1.05	1.058	1.056
3240	1.011	1.043	1.042	1.033	1.053	1.055	1.043	1.055	1.054
3420	1.053	1.062	1.057	1.055	1.058	1.063	1.055	1.06	1.057
3480	1.045	1.052	1.038	1.047	1.057	1.061	1.052	1.059	1.057
3660	1.06	1.068	1.067	1.062	1.059	1.066	1.059	1.061	1.058
3720	1.045	1.061	1.059	1.042	1.054	1.057	1.046	1.056	1.055
3960	1.067	1.072	1.071	1.071	1.061	1.069	1.064	1.063	1.059
4020	1.049	1.062	1.061	1.047	1.056	1.06	1.05	1.058	1.056
4140	1.06	1.069	1.067	1.062	1.06	1.067	1.06	1.061	1.059
4260	1.071	1.074	1.073	1.076	1.064	1.073	1.069	1.065	1.061
4320	1.063	1.07	1.069	1.066	1.052	1.061	1.054	1.059	1.057
4560	1.072	1.075	1.074	1.077	1.064	1.073	1.07	1.065	1.061
4620	1.069	1.074	1.073	1.074	1.062	1.071	1.067	1.064	1.06
4740	1.072	1.075	1.074	1.078	1.064	1.073	1.07	1.065	1.061
4800	1.069	1.073	1.072	1.073	1.061	1.069	1.064	1.063	1.059
4860	1.072	1.075	1.074	1.078	1.064	1.073	1.07	1.065	1.061
4920	1.07	1.074	1.073	1.075	1.049	1.065	1.064	1.061	1.058
5040	1.072	1.075	1.074	1.077	1.067	1.074	1.07	1.065	1.061
5100	1.07	1.074	1.073	1.075	1.064	1.061	1.061	1.059	1.057
5160	1.072	1.075	1.074	1.077	1.068	1.075	1.07	1.066	1.062
5280	1.071	1.074	1.074	1.076	1.069	1.071	1.067	1.051	1.054
5340	1.072	1.075	1.074	1.078	1.072	1.078	1.072	1.07	1.064
5400	1.072	1.075	1.074	1.078	1.072	1.078	1.072	1.07	1.064

- For Bus 30 to 39 (Generator Buses)

Table 22: IEEE 39 Bus System, Bus 30 to 39 Voltage w.r.t DR at 0.5<PF<0.6

DR	**Bus 30**	**Bus 31**	**Bus 32**	**Bus 33**	**Bus 34**	**Bus 35**	**Bus 36**	**Bus 37**	**Bus 38**	**Bus 39**
[MW]	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**
0	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
240	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03

540	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
660	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
720	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
960	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
1020	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
1140	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
1200	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
1440	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
1740	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
1800	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
2220	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
2280	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
2340	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
2700	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
2760	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
2880	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
2940	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
3000	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
3180	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
3240	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
3420	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
3480	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
3660	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
3720	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
3960	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
4020	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
4140	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
4260	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
4320	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
4560	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
4620	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
4740	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
4800	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
4860	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
4920	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
5040	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
5100	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
5160	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
5280	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
5340	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03
5400	1.05	0.982	0.984	0.997	1.012	1.049	1.064	1.028	1.027	1.03

The following table lists the total Generation, Losses and Loads for each step of DR applied at above mentioned PF.

Table 23: Power Generation vs Load and Loss

DR	Generation		Losses		Load	
[MW]	[MW]	[MVAR]	[MW]	[MVAR]	[MW]	[MVAR]
0	6304.9	2265.8	50.63	1147.8	6254.2	2217.8
240	6071.1	1977.5	56.91	1189.3	6014.2	1888.2
540	5791.5	1824.3	77.25	1441.75	5714.2	1476.3
660	5683.4	1824.5	89.14	1602.2	5594.2	1311.5
720	5634.3	2631.7	100.07	1842.3	5534.2	1841.9
960	5397.6	2248.4	103.33	1846.3	5294.2	1474.6
1020	5332	2074.6	97.7	1772.4	5234.2	1382.8
1140	5203.3	1764.7	89.08	1660.58	5114.2	1199.2
1200	5138	2926.8	83.74	1591	5054.2	2433.5
1440	4882.7	2388	69.46	1399.2	4814.2	2092.3
1740	4581.9	1915.6	67.6	1350.6	4514.2	1665.8
1800	4518.8	1765.8	64.5	1288.5	4454.2	1580.4
2220	4088.5	939.6	54.32	1067.3	4034.2	983.3
2280	4034.3	1601.1	60.11	1189.7	3974.2	1487.8
2340	3972.8	1455.6	58.62	1145.1	3914.2	1394
2700	3611.8	749.2	57.53	1038.2	3554.2	830.6
2760	3550.1	1024.2	55.9	1024	3494.2	1105.9
2880	3426	802.4	51.8	976.5	3374.2	944
2940	2261.6	651.4	47.4	913.8	3314.2	863
3000	3300.2	900.6	46	895.2	3254.2	1109.6
3180	3110.7	468.8	36.5	755.5	3074.2	847.3
3240	3049.7	707.4	35.4	748.8	3014.2	1081.9
3420	2863.4	292.9	29.2	646.6	2834.2	787.8
3480	2801.9	483.9	27.7	628.2	2774.2	991.7
3660	2617.9	128.2	23.7	559.6	2594.2	715.5
3720	2559.6	468.2	25.3	585.5	2534.2	1010.2
3960	2316.7	-24.7	22.4	534.2	2294.2	596.9
4020	2255.1	293.9	20.9	504.3	2234.2	927.7
4140	2131.1	36.3	16.9	421.8	2114.2	765.7
4260	2008.2	-198	14	361.6	1994.2	603.7
4320	1948.1	165.8	13.8	357	1934.2	950.7
4560	1705.1	-241.5	10.9	292.8	1694.2	630.7
4620	1645.5	-56.9	11.2	281.9	1634.2	816.7
4740	1524.7	-300	10.5	236	1514.2	630.7
4800	1464	-208.6	9.8	213.7	1454.2	737.7
4860	1403.4	-319.1	9.2	194	1394.2	653.7
4920	1345.1	-130.9	10.9	189.5	1334.2	837.6
5040	1225.8	-316.6	11.55	180.9	1214.2	668.6
5100	1166	-227.5	11.7	172.2	1154.2	758.6
5160	1106.2	-319.5	11.9	169.4	1094.2	677.6
5280	986.5	-242.5	12.3	151.1	974.2	767.4
5340	927	-340.1	12.8	142.6	914.2	685.5
5400	866.7	-326.9	12.5	136.2	854.2	704.6

Graphs of Bus Voltages are as follows:

- Bus 1 (Representative of the trend)

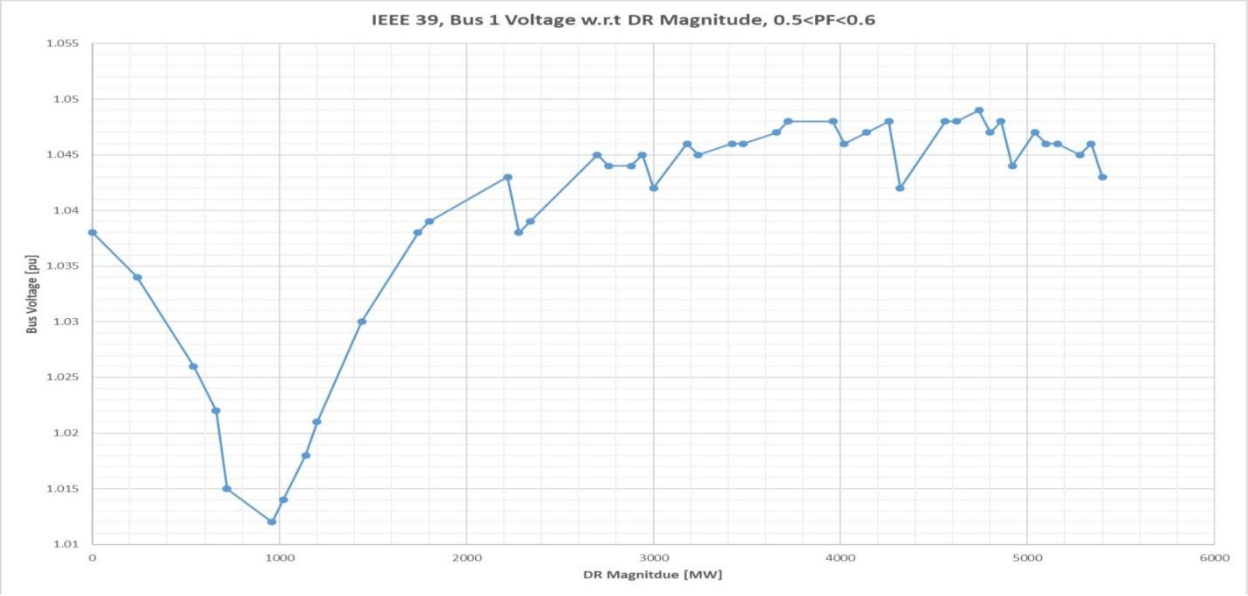

Figure 23: IEEE 39 Bus system, Bus 1 Voltage w.r.t DR at 0.5<PF<0.6

- Bus 1 to Bus 29

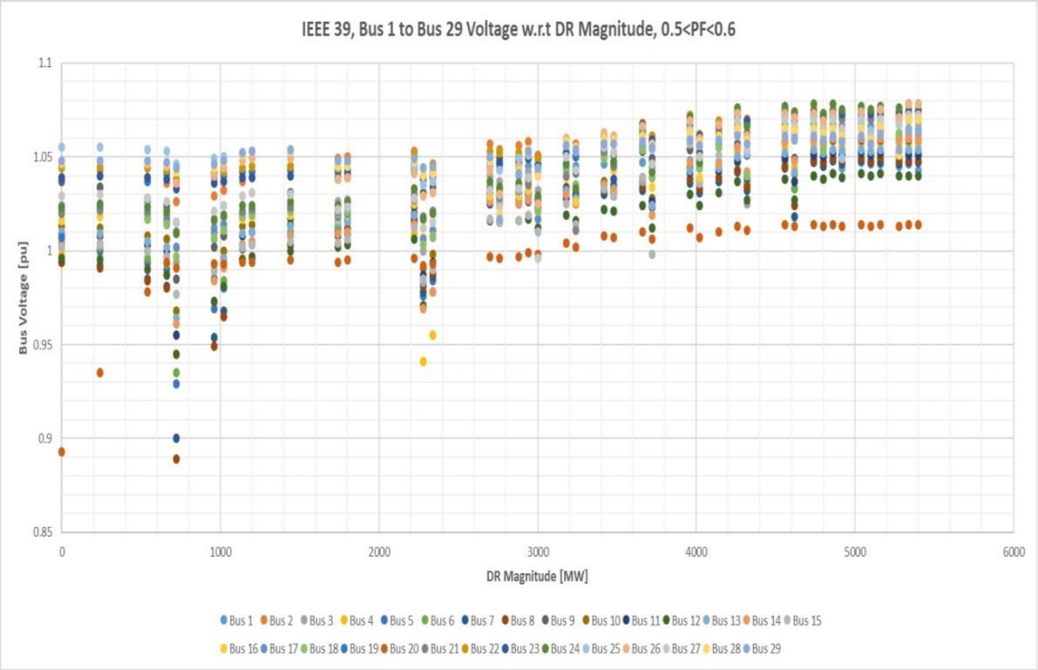

Figure 24: IEEE 39 Bus System, Bus1 to 29 Voltage w.r.t DR at 0.5<PF<0.6

- Bus 30 to Bus 39 (Generator Buses)

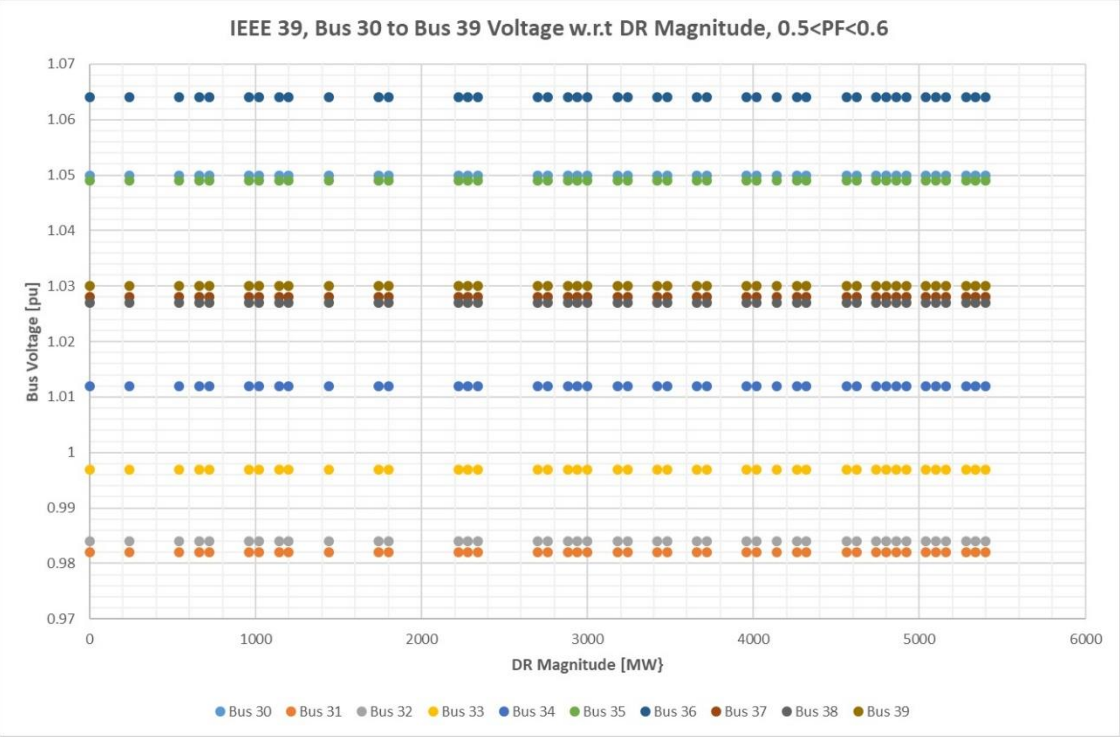

Figure 25: IEEE 39 Bus System, Bus 30 to 39 Voltage w.r.t DR at <0.5PF<0.6

4.5.3 Comparison of Bus Voltages at different DR Power Factor

The following table and graph show the difference between Bus Voltages as DR Load Power Factor is varied. This data is for Bus 1 only and is intended for a representation of general trend.

Table 24: IEEE 39 Bus System, Bus 1 Voltage at Different PF

DR [MW]	Bus 1 (0.9PF)	Bus 1 (0.5PF)
0	1.039	1.038
240	1.035	1.034
540	1.026	1.026
660	1.022	1.022
720	1.02	1.015
960	1.014	1.012
1020	1.016	1.014
1140	1.018	1.018
1200	1.021	1.021
1440	1.031	1.03
1740	1.038	1.038
1800	1.039	1.039
2220	1.044	1.043
2280	1.044	1.038

2340	1.044	1.039
2700	1.045	1.045
2760	1.045	1.044
2880	1.045	1.044
2940	1.046	1.045
3000	1.046	1.042
3180	1.047	1.046
3240	1.047	1.045
3420	1.048	1.046
3480	1.048	1.046
3660	1.048	1.047
3720	1.048	1.048
3960	1.049	1.048
4020	1.049	1.046
4140	1.05	1.047
4260	1.05	1.048
4320	1.05	1.042
4560	1.051	1.048
4620	1.051	1.048
4740	1.051	1.049
4800	1.051	1.047
4860	1.051	1.048
4920	1.051	1.044
5040	1.051	1.047
5100	1.051	1.046
5160	1.051	1.046
5280	1.05	1.045
5340	1.05	1.046
5400	1.055	1.043

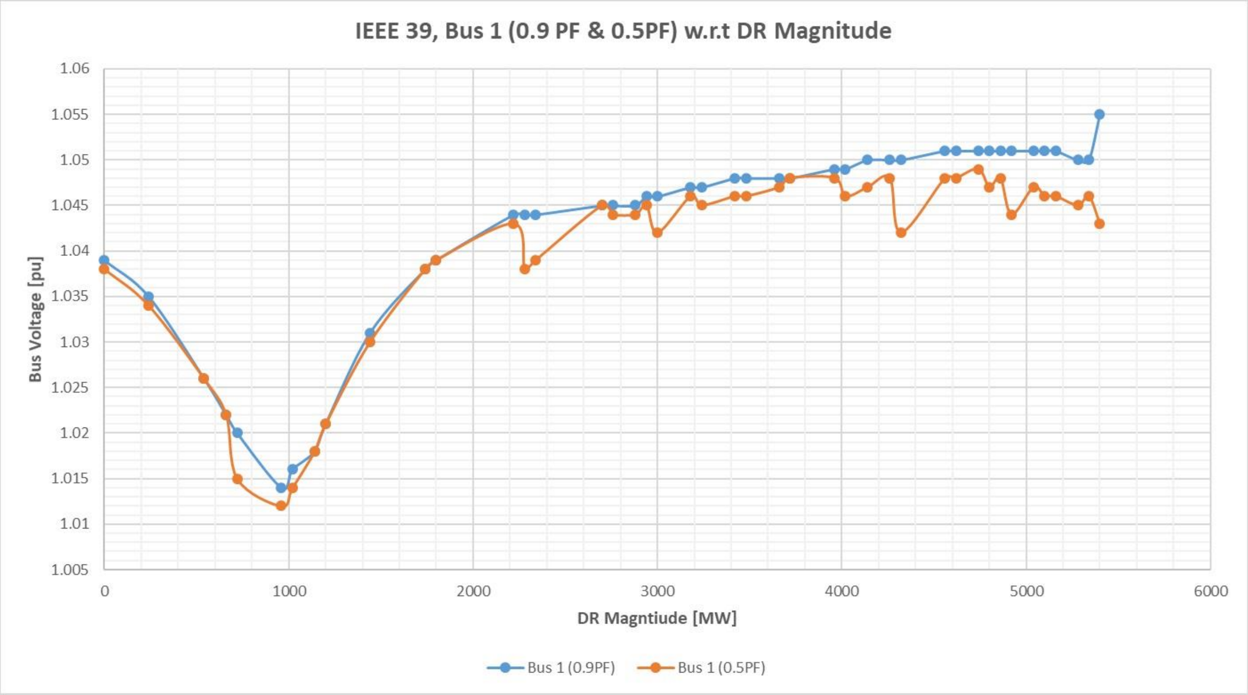

Figure 26: IEEE 39 Bus System, Bus 1 Voltage at Different PF

4.6 Load Flow with a Shunt Capacitor

An analysis was performed on two IEEE systems i.e. 5 Bus and 9 Bus, in order to enhance the observable effect of Bus overvoltage caused by application of DR. This has been executed via the following procedure

- A load bus was selected that has (1) No Generator attached to it and (2) Where possible, is adjacent to buses and generators attached to them. Rationale behind this is to try to isolate the effects of DR application to a certain region. This will enable to limit the effect of DR on other buses in the system except our targeted load bus.
- Load power factor was changed to be between 0.5PF and 0.6PF. A Load Flow was performed, and bus voltages were considered to be as base case.
- A generator was removed, to simulate a contingency, and DR applied exclusively on the load bus. In case the load rating was not enough to balance the removed generator rating, DR was performed on another load bus. Care was taken to keep this value to be a minimum incases it was not completely avoidable. Load Flow was performed to calculate the bus voltages.
- A shunt capacitor was added to the targeted load bus. This was done to ensure that the voltages will increase due to the excessive reactive power and a change in voltages is more pronounced. Load Flow was performed for two values of the Capacitor i.e. 30MVAr and 90MVAr.
- This analysis was repeated with the removal of the Generators from other buses connected to the targeted load bus.

4.6.1 IEEE 5 Bus System

Figure 27 depicts the default IEEE 5 Bus system that is packaged with MATPOWER. DR is performed on Load Bus 2 with a decreased Power Factor of less than 0.6PF but higher than 0.5PF, this modified network is represented in Figure 28. Generators on Bus 1 and Bus 3 are removed respectively for this case.

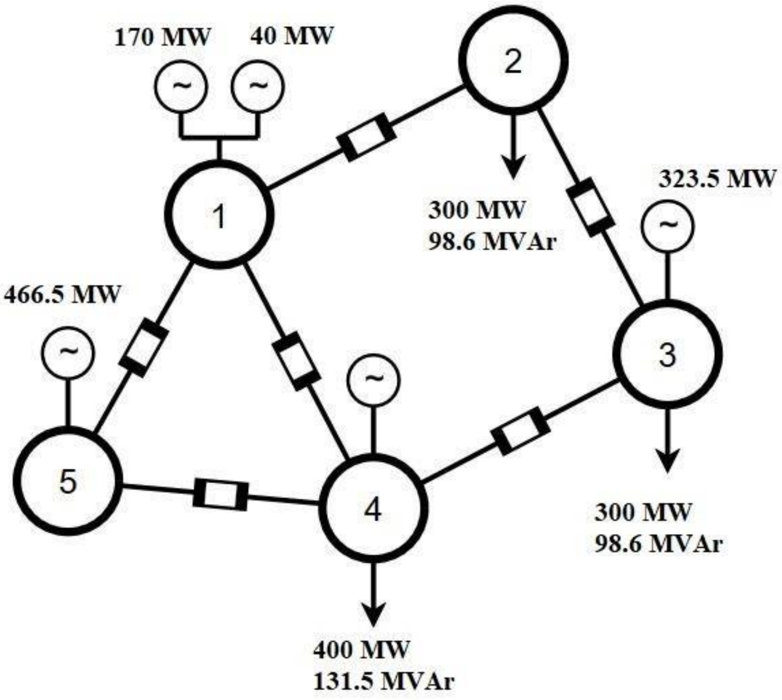

Figure 27: IEEE 5 Bus System Packaged with MATPOWER

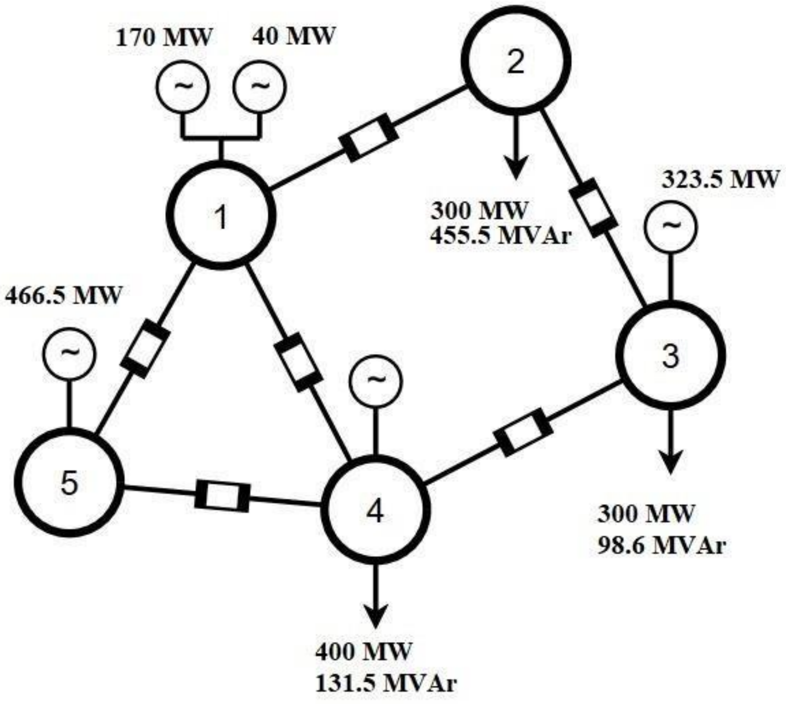

Figure 28: IEEE 5 Bus System with Load Bus 2 PF Decreased

These were the scenarios for this case.

1. **Generators at Bus 1 Removed**

   a. Generators at Bus 1 (210MW) were removed to simulate a contingency and an equivalent DR was applied at Bus 2. Load flow was performed. This system is represented in Figure 29 .

   b. A Shunt Capacitor (30MVAR and 90MVAR) to Bus 2. Load flow was performed again. This system is depicted in Figure 30.

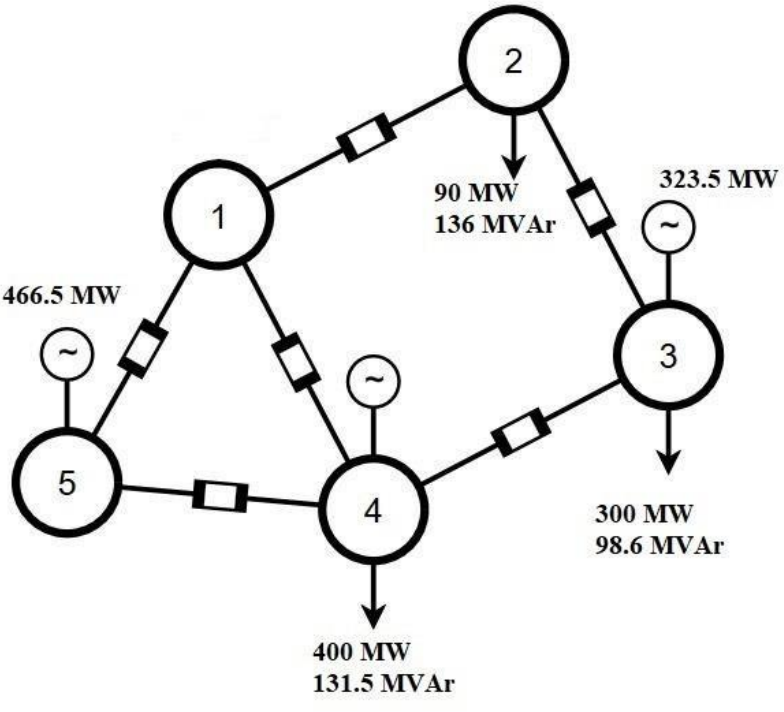

Figure 29: IEEE 5 Bus System with Generators at Bus 1 Removed

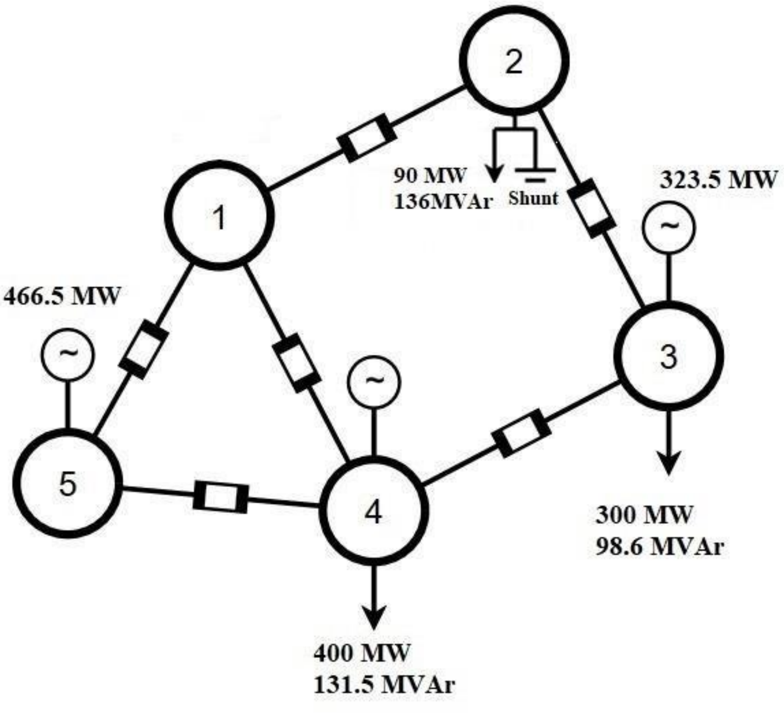

Figure 30: IEEE 5 Bus System with Shunt Capacitor at Bus 2

c. These are the Bus Voltages

Table 25: Bus 2 Voltages for Scenario 1

	Bus 1 [pu]	**Bus 2 [pu]**	**Bus 3 [pu]**	**Bus 4 [pu]**	**Bus 5 [pu]**
No DR	1	0.96	1	1	1
210 MW DR	0.998	0.988	1	1	1
30 MVAR Cap	0.998	0.99	1	1	1
90 MVAR Cap	0.999	0.995	1	1	1

2. Generator at Bus 3 Removed

a. Generator at Bus 3 (323.5MW) was removed, as depicted in Figure 31, and to balance this contingency, DR of 299MW was applied on Bus 2 (in order to simulate a very high DR penetration, most of the load was shed). To balance total Generation and Load respectively, DR of about 24.5MW was applied at Bus 4 (which had an original load of 400MW). Load Flow was performed.

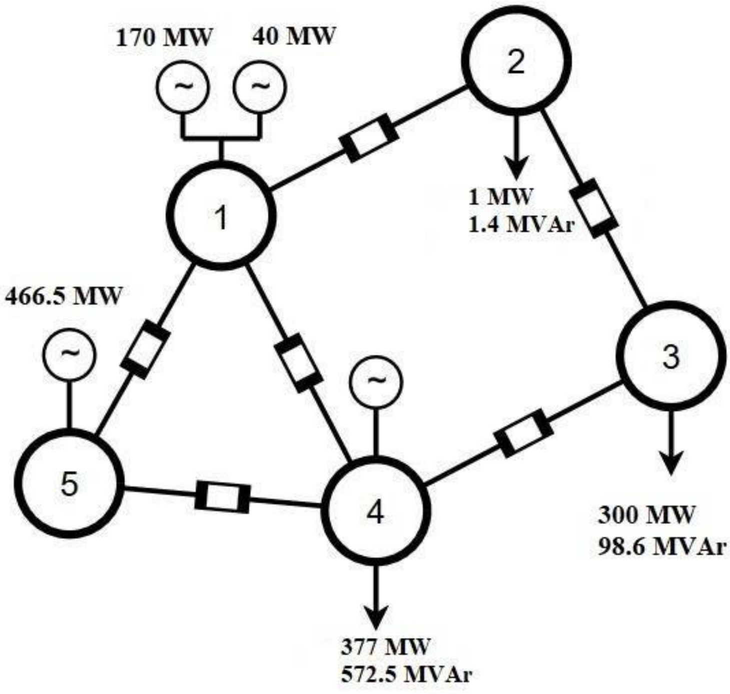

Figure 31: IEEE 5 Bus System with Generator at Bus 3 Removed

b. A Shunt Cap (30 MVAR and 90 MVAR) was added to Bus 2. Load Flow was performed. This system configuration is depicted in Figure 32.

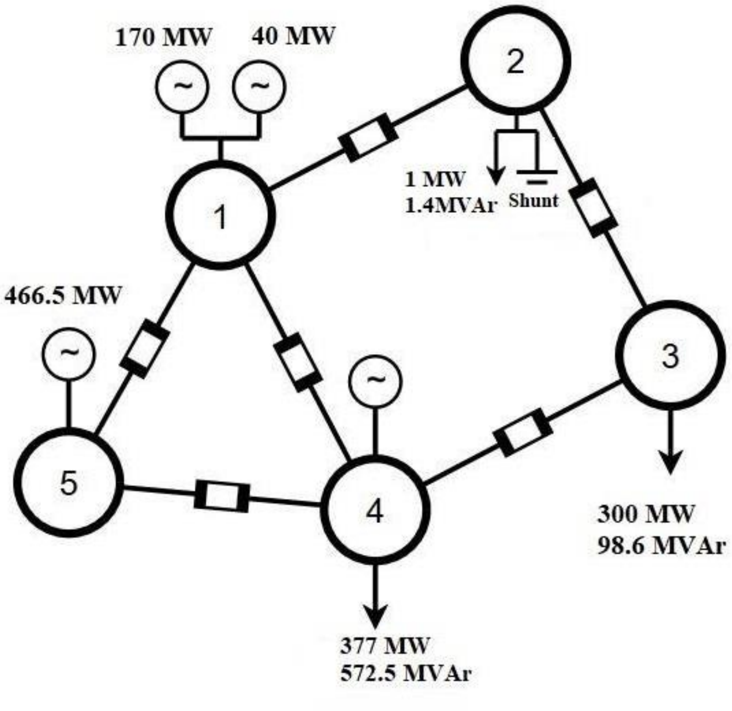

Figure 32: IEEE 5 Bus System with Shunt Capacitor on Bus 2

c. These are the Bus 2 pu Voltages

Table 26: Bus 2 Voltages for Scenario 2

	Bus 1	**Bus 2**	**Bus 3**	**Bus 4**	**Bus 5**
	[pu]	**[pu]**	**[pu]**	**[pu]**	**[pu]**
No DR	1	0.96	1	1	1
323 MW DR	1	0.982	0.976	1	1
30 MVAR Cap	1	0.987	0.98	1	1
90 MVAR Cap	1	0.997	0.987	1	1

3. <u>Generators at Bus 1 and Generators at Bus 3 Removed</u>

a. This is essentially a sub-case of Scenario 1.

b. Gens at Bus 1 are removed (210MW) and another 80MW from Gen 3 are decreased. DR at Bus 2 is applied (total DR of 290MW). Load Flow is performed at both instances.

c. Shunt Capacitor is later added (30MVAR/90MVAR) and Load Flow performed again.

d. Bus 2 Voltages are as follow

Table 27: Bus 2 Voltages for Scenario 3

	Bus 1 [pu]	Bus 2 [pu]	Bus 3 [pu]	Bus 4 [pu]	Bus 5 [pu]
No DR	1	0.96	1	1	1
210 MW DR	0.998	0.988	1	1	1
80 MW DR	1	0.999	1	1	1
30 MVAR Cap	1	1.001	1	1	1
90 MVAR Cap	1	1.006	1	1	1

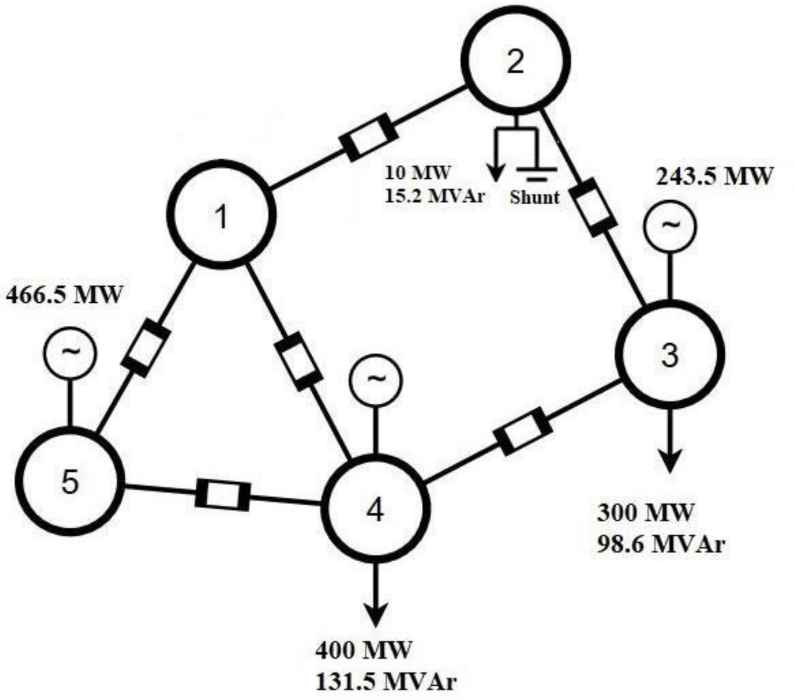

Figure 33: IEEE 5 Bus System with Gens at Bus 1 removed, 80MW at Gen 3 Dec, Shunt Cap at Bus 2

4.6.2 IEEE 9 Bus System

The default IEEE 9 Bus system, that is packaged with MATPOWER, was modified and Power Factor of Load Bus 7 was decreased to be between 0.5PF and 0.6PF, this is depicted in Figure 34. Generators on Bus 2 and Bus 3 are removed respectively for this case. *No DR* in the results represent a base case where Load Flow is performed on the system with Load Bus 7.

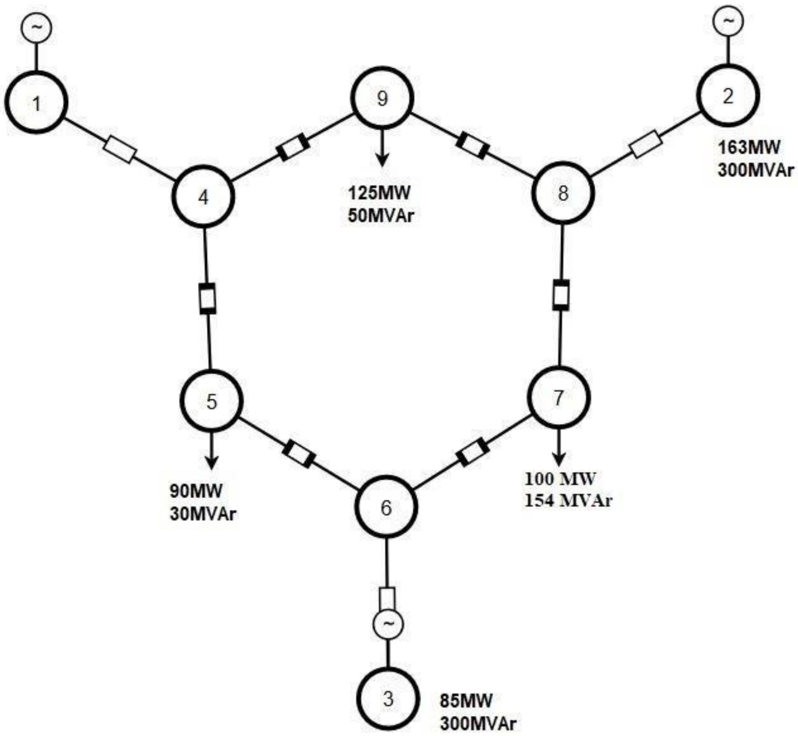

Figure 34: IEEE 9 Bus System with Load Bus 7 PF Decreased

These were the scenarios for this case.

1. **<u>Generator at Bus 3 Removed</u>**

   a. Generator at Bus 3 (85MW) was removed to simulate a contingency and an equivalent DR was applied at Bus 7.

   b. A Shunt Capacitor (30MVAr and 90MVAr) to Bus 7. Load flow was performed again. This system is depicted in Figure 35.

   c. Bus Voltages are as follows

Table 28: Results for IEEE 9 Scenario 1

	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6	Bus 7	Bus 8	Bus 9
	[pu]	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**
No DR	1	1	1	0.974	0.954	0.97	0.887	0.954	0.932
85 MW DR	1	1	1.018	0.991	0.984	1.018	1.006	1.005	0.962
30 MVAr Cap	1	1	1.046	0.998	1	1.046	1.041	1.02	0.973
90 MVAr Cap	1	1	1.107	1.015	1.034	1.107	1.116	1.054	0.998

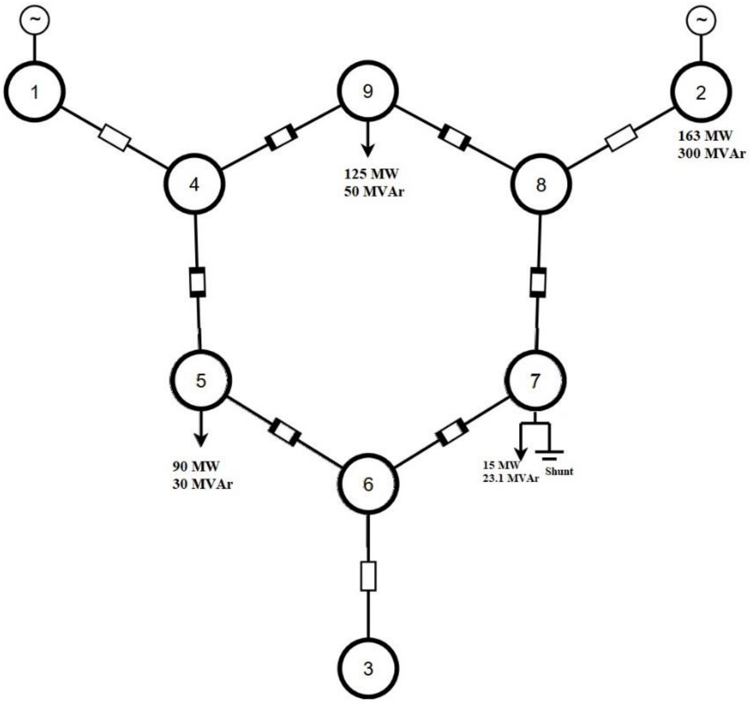

Figure 35: IEEE 9 Bus System with Shunt Capacitor at Bus 7

2. Generator at Bus 2 Removed

a. Generator at Bus 2 (163MW) was removed to simulate a contingency and a DR of 99 MW was applied at Bus 7 (to simulate very high DR penetration). Since the Generator has higher rating than Load at Bus 7, 64MW of DR was divided on Load Bus 5 and 9 respectively according to the ratio of their Active Loads i.e. 27MW at Bus 5 and 37MW at Bus 9 respectively. Care was taken to reduce the Power Factor for these Buses as well. Please refer to Figure 36 for the network representation. Load Flow was performed to calculate the Bus Voltages.

b. A Shunt Capacitor was added on Bus 7 and Load Flow was performed for two Capacitor values i.e. 30MVAr and 90MVAr.

c. Bus voltages are as follows

	Bus 1	**Bus 2**	**Bus 3**	**Bus 4**	**Bus 5**	**Bus 6**	**Bus 7**	**Bus 8**	**Bus 9**
	[pu]	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**
No DR	1	1	1	0.974	0.954	0.97	0.887	0.954	0.932
163 MW DR	1	0.982	1	0.924	0.881	0.977	0.954	0.928	0.832
30 MVAr Cap	1	0.961	1	0.933	0.893	0.99	0.992	0.961	0.852
90 MVAr Cap	1	1.032	1	0.953	0.919	1.02	1.075	1.032	0.896

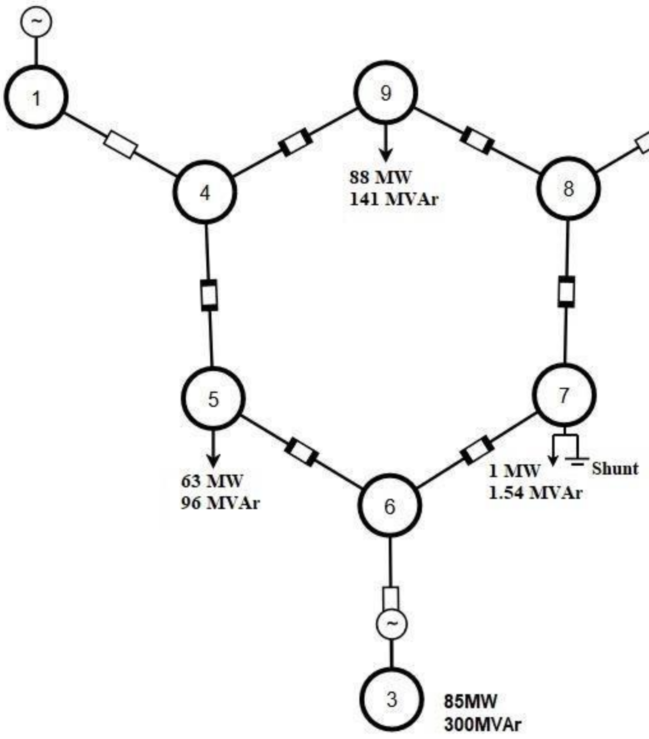

Figure 36: IEEE 9 Bus System with Generator at Bus 2 Removed and Shunt Capacitor Added

Table 29: Bus Voltages

	Bus 1	**Bus 2**	**Bus 3**	**Bus 4**	**Bus 5**	**Bus 6**	**Bus 7**	**Bus 8**	**Bus 9**
	[pu]	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**	**[pu]**
No DR	1	1	1	0.974	0.954	0.97	0.887	0.954	0.932
163 MW DR	1	1.048	1	1.012	1.012	1.028	1.046	1.048	1.01
30 MVAr Cap	1	1.08	1	1.02	1.022	1.042	1.085	1.08	1.027
90 MVAr Cap	1	1.152	1	1.037	1.045	1.072	1.17	1.152	1.065

4.7 Summary

This chapter contains the analysis of application of DR on electric power systems and it was observed that

1. Decreasing DR Magnitude will increase the Bus Voltages

2. Decreasing DR PF will cause variations in Bus Voltages, but not always enough to exceed Steady State Upper Limit i.e. 1.05pu.

   - This can be alleviated by repeating the analysis with the presence of a shunt Capacitor.

3. DR Magnitude has extensive effect on Bus Voltages, however high DR does not **always** corelate to high Bus voltage. Other factors need to be investigated for the reason behind this.

4. DR Location is significant in low PF loads.

Chapter 5
Conclusion and Future Recommendations

5.1 Conclusion

Demand Response (DR) is an active research area and the purpose of this study was to understand the effect on a high voltage system when active power balancing is provided via applying DR on an IEEE Bus System. Bus Voltages were considered as they are a good measure of system reliability.

My conjecture stated that DR activity can provide active power balance but when system load is exceedingly low either due to some contingency or due to application of DR and when coupled with the presence of Ferranti Effect, the excess reactive power can spike the bus voltage past their thresholds. Another aspect of this thesis was the second part of the conjecture i.e. whether there are any effects of DR application with respect to its location in the system, magnitude and type of load i.e. composition.

MATPOWER was used to perform the analyses. Test cases of IEEE 5, IEEE 9 and IEEE 39 system were selected based on their complexity, base voltage and base results. It was ensured that sufficient variability exists in the electrical networks.

Based on the results in previous chapter, it has been observed that

1. Decreasing DR Magnitude will increase the Bus Voltages

2. Decreasing DR PF will cause variations in Bus Voltages, but not always enough to exceed Steady State Upper Limit i.e. 1.05pu.

    This can be alleviated by repeating the analysis with the presence of a shunt Capacitor.

3. DR Magnitude has extensive effect on Bus Voltages, however high DR does not **always** corelate to high Bus voltage. Other factors need to be investigated for the reason behind this.

4. DR Location is significant in low PF loads.

These results were more or less same to what was thought out initially. However, as mentioned in the results of IEEE 9 Bus system, a Shunt Capacitor was used to unmask the potential high bus voltages.

What can be the benefit of these results? It reconfirms the suitability of using DR as means to ensure system reliability in case of contingencies. Moreover, it serves as a guide for grid operators and planners to take into account the potential high or low voltage when DR is applied. With more emphasis on transition to a smart and green electricity grid, DR will be utilized more and more by utilities in very near future.

5.2 Future Work

This thesis was focused on only one aspect of system reliability i.e. voltage levels. It is recommended that same study be conducted for system frequency as well. This will ensure that all aspects of power system reliability are analyzed before widespread adoption of DR as a contingency reserve.

Moreover, another aspect to be studied is the potential low voltage that may result when DR is used to balance increasing power generation. Such scenario may seem far fetched but with rapid rise of intermittent wind and PV power sources, DR can provide an alternative to expensive grid-scale battery storage. In such cases, absence of reactive power may cause the bus voltages to decrease. In addition to, as with this thesis, such DR application should be analyzed with respect to DR location, composition and magnitude as well.

Lastly, with bilateral electricity markets in vogue now, it is only a matter of time when DR sanctioned load for contingencies will also be economically analyzed as well. Author of this thesis recommends including the price aspect in the calculations as well.

Best of luck!