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The National Conference of State Legislatures NCSL declares that 29 states have been active in adopting and increasing renewable portfolio standards. Present renewable portfolio standards require utilities to increase integration of renewable energy sources such as photovoltaic (PV). The increased penetration of PV systems is expected to destabilize the power system. Therefore, this thesis studies the steady state voltage of Western Electric Coordinating Council (WECC) as the penetration level of the PV system increases to find the point where the penetration level makes the system unstable. In addition, this study serves to pinpoint the violated transmission lines as the penetration level increases, while also identifying why this violation occurs. The study is divided into two scenarios: integration of a rooftop only PV system at unity power factor and integration of both rooftop and utility scale PV systems. The study uses MATpower simulation program to solve the system power flow for each scenario. The results show that when we integrate a rooftop only PV system, the steady state voltage in the light loaded buses becomes unstable as the penetration level increases. However, integrating both rooftop and utility scale PV systems enhance the system stability. Also, the transmission line violations are observed while PV system penetration level increases.

Determining The Impact of Photovoltaic Generation on Power Systems

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Chapter 1: INTRODUCTION

Traditionally, generation units produce electrical energy. Then, this energy is transported by the power grid to the consumer. Typically, the electric energy flows in one direction from the generation units to the consumer. Although the power system has been in this configuration for years, it still performs effectively due to designs, standards, and regulations that have been made. Lately, many rooftop Photovoltaic (PV) systems have been connected to the distribution network. The penetration level of rooftop PV systems is expected to increase [1] [2]. Therefore, the power system configuration starts changing. These changes may lead to stability problems because the power grid was not designed to have distributed generations such as PV systems [3]. In addition, as the penetration level of PV systems increases, some of the conventional generation will switch off. This conventional generation may be replaced by utility scale PV systems, rooftop PV systems, or both. Replacing the conventional generation by PV systems that are located at load side may lead to a lack of reactive power. Current standards, such as IEEE 1547 and UL 1741 recommend that PV inverters should not control the voltage at the point of common coupling (PCC) [4] [5]. In other words, the rooftop

PV systems will produce real power and zero reactive power. The high penetration of PV systems into the distribution network will change the energy flow direction and the configuration of the system. These changes may cause voltage rise, voltage fluctuations, reverse power, and harmonic effect problems in the distribution system. Understanding these problems will help us to find the proper solutions.

The integration of large scale Photovoltaic systems affects the distribution system, transmission system and production units. Most of the research investigations studied the impact on the distribution system. Both references [6] and [7] study the problem of the voltage rise. According to reference [6], the injected power is proportional to the resistive part of the source impedance at the point of connection, and the relative voltage rise is approximately equal to:

$$\frac{\Delta V}{V} = \frac{R \times P_{gen}}{V^2} \tag{1.1}$$

where R is the source resistance at the terminals of the generator, P_{gen} the injected active power, and V the nominal voltage. The effect of voltage rise can be significant when large PV systems are connected near the end of long or light load feeders [7]. Sources [8], [9] and [10] focus on the voltage fluctuation effect.

Fast variations in voltage magnitude are often referred to as voltage fluctuation or flickers. Voltage fluctuates with solar irradiance. Voltage fluctuation can either be short-term due to passing clouds or long-term due to seasonal variation. Short-term fluctuation causes power quality issues [8]. For a high penetration of the PV systems in a limited area, the output of PV system could fluctuate separately and simultaneously with load variation. As a consequence, voltage fluctuation in the line could increase beyond the load fluctuations which may lead to technological issues [9]. Voltage fluctuation has a significant effect on the voltage profile of the feeder, which can lead to over functioning of the load tap changers (LTC) of transformers, line voltage regulators (VR) and capacitor banks, which may cause additional step-voltage variations [10]. Voltage fluctuation can be noticeable on weak feeders and when PV systems are located at the end of long feeders. High penetration of PV systems in distribution feeders can offset local feeder loads. As a consequence, the power flow reverses and the feeder will transport power to other feeders or transmission networks. Most of the distribution systems are designed to have power flow in one direction, and for this reason, the overcurrent protection coordination of the distribution systems may be affected [11]. Reference [12] discusses the harmonic effect. PV systems use inverters to interface with the power grid. Inverters tend to contribute harmonics into the network depending on the technology they use. According to [12], “inverters coupled with a transformer tend to have a higher harmonic injection to the system compared to those with none”.

The cited works effectively present the problems in the distribution systems that are associated with high PV penetration levels. It is important to enunciate, however, the effect of increased penetration levels of PV systems undermine transmission system stability. Studying the impact of increased penetration on the large system is a new topic; therefore, research regarding this topic is limited.

The thesis focuses more on identifying how many penetration levels the power system can handle to continue functioning. To achieve this aim, it studies the impact of increased penetration on voltage stability and the transmission lines. The goals of this work are:

- Establish the correlation between PV penetration levels and steady state voltage magnitudes.
- Locate the unstable buses.
- Identify the relationship between PV penetration levels and power flow in the transmission lines.

- Locate the violated transmission lines.

The following list presents the major finding in this work:

- With increased PV penetration levels, the steady state voltage follows a quadratic behavior.
- Increased PV penetration level influences the light loaded buses more.
- The lack in the reactive power is the major cause of the instability in the system.
- The real power starts to reverse after 15% penetration level.
- With increased PV penetration levels, the number of the violated transmission lines increases.
- The utility scale PV systems enhance the system stability.

These goals will help the operator's companies to overcome these issues. Also, it will be important for regulators or system planners to know these issues in order to design the proper rules and regulations [13].

This thesis is organized to effectively demonstrate the study, its results, and overall effect of the research. Consequently, by regarding the research, it becomes clear that integrating both rooftop and utility scale PV systems improve the system stability.

Chapter 2: BACKGROUND

This chapter provides a basic background of power systems in order to understand the impact of increased PV penetration. The first section explains the fundamentals of the power system. The second section defines the power system terminology.

2.1 Power System Fundamentals

The well known components in a power system include the voltage and the current; however, it is important to enunciate the concept of real power (P), reactive power (Q), complex power (S), power factor ($P.F$), impedance (Z), and admittance (Y). The real power P is measured in watt (W) and physically defined as the rate in which energy absorbed by resistive load . Q is Measured in volt-amp reactive (VAR). It is the maximum value of the instantaneous power absorbed by reactive load [14]. The sum of the real power and the reactive power is the complex power

S which is the product of the voltage and the conjugate of the current [15].

$$
\begin{aligned}
S = VI^* = [V\angle(\delta)][I\angle(\beta)]^* = VI\angle\delta - \beta \\
= VIcos(\delta - \beta) + jVIsin(\delta - \beta)
\end{aligned}
\tag{2.1}
$$

The term $cos(\delta - \beta)$ is called the power factor in a power system . According to [14] the power factor is the ratio of the power that it draws from the main supply and the power that it actually consumes.

Another important component in the electric system is electrical impedance (Z).

$$Z = R + jX \tag{2.2}$$

Z consists of real and imaginary components. The real component is known as resistance. The resistance measures the capacity of the conductor to impede the flow of the current [15]. The imaginary part called reactance, measures the opposition of a circuit element's inductance or capacitance to alternating current [16].

The reciprocal of the impedance is admittance (Y). Y has both real and imaginary components. The real component is known as conductance (G). The conductance is reciprocal of R and it measures the conductor's ability to pass the current [16]. The imaginary component is called susceptance (B), and it measures the ease in which alternate currents pass through the conductor. G and B are reciprocal of R and X.

$$Y = Z^{-1} = \frac{1}{R + jX} = G + jB \tag{2.3}$$

The conventional electric power systems consist of three subsystems: generation, transmission, and distribution or loads. The generation units are hundred of miles far from the loads. The two subsystems are connected through transmission lines. The transmission lines are linked by nodes that the power system engineers call buses. The buses are classified by three types:

1. Swing\Slack bus: The power system has only one slack bus. The slack bus has the voltage (V_k) and the angel (δ_k) as input data and the net real power (P_k) and the net reactive power (Q_k) are unknown.

2. Load bus: Most of the buses in the power system are load buses. Both the P_k and Q_k are known so this type of bus is also called PQ bus. V_k and δ_k are unknown in this type.

3. Voltage controlled bus: In this type, P_k and V_k are known and Q_k and δ_k should be computed. This type of buses also called PV bus.

The letter k represents the bus number. P_k and Q_k are the net real and reactive power at bus k. That is,

$$P_k = P_{Gk} - P_{Dk} \tag{2.4}$$

$$Q_k = Q_{Gk} - Q_{Dk} \tag{2.5}$$

All three subsystems have to operate in synchronism as one system. Understanding these three subsystems and how they are related help clarify the impact of integrating new source to the power system.

2.2 Terminology

V Voltage

I Current

$\boldsymbol{\delta}$ Voltage Phase Angle

$\boldsymbol{\beta}$ Current Phase Angle

P Real Power

Q Reactive Power

S Complex power

P.F Power Factor

Chapter 3: METHODOLOGY

My research studied the simplified case of Western Electric Coordinating Council (WECC) [17]. In this work, I used a Matpower program to simulate the power flow solution of the WECC system. This Matpower program encompasses MATLAB M-files to solve issues regarding power flow. One of the significant advantages of Matpower is the ability for the user to add a new algorithm or modify the source code. In addition, the Matpower package is free. I integrated PV systems into WECC. Then, I studied the voltage stability and the transmission lines violations. To conduct this work, I divided it into two scenarios, focusing on integration of rooftop only PV system at unity power factor and integration of both rooftop and utility scale PV systems. Each scenario examined different penetration levels.

3.1 Integration of Rooftop Only PV System

Because the penetration levels of rooftop PV systems in the distribution system have increased recently, I created a scenario that integrated solar energy using just the rooftop PV systems. These systems worked at a unity power factor. A unity power factor means the PV system will produce only real power and the reactive power will be zero. This scenario studied different penetration levels of PV systems. The penetration levels started at zero percent and then gradually increased by 5% until it reached 25%. I integrated the PV system as negative power demand. The amount of PV penetration differed from zone to zone. The highest penetration was in the first zone that had the highest power demand. The WECC model was divided into three zones. The first zone had three areas: Canada, Montana, and Idaho. The second zone had five areas: WAPA UC, New-Mexico, Northwest, Pace, and Arizona. The third zone had three areas: PG&E, South California (SOCALIF), and LADWP. In order to calculate the PV integration for each zone, I had to calculate the total power demand($P_{tot-demand}$) of the whole system, then find the percentage of the power demand for each zone which is expressed as follows.

$$Zone\,\% = \frac{zone\,(X)\,power\,demand}{P_{tot-demand}} \tag{3.1}$$

After that, I calculated the PV penetration level using this formula:

$$PV_{tot-gen} = PV_{pen-level}(\%) \times P_{tot-demand} \tag{3.2}$$

PV generation / Zones	5%	10%	15%	20%	25%
Zone 1	1291.9 MW	2583.9 MW	3875.8 MW	5167.7 MW	6459.7 MW
Zone 2	613.38 MW	1226.8 MW	1840.1 MW	2453.5 MW	3066.9 MW
Zone 3	1134 MW	2267.9 MW	3401.9 MW	4535.8 MW	5669.8

Table 3.1: PV Generation for Each Zone at Different Penetration Levels

Then, I calculated the PV penetration for each zone.

$$PV_{tot-gen}\ for\ each\ zone = PV_{tot-gen} \times Zone\ (X)\% \tag{3.3}$$

Table 3.1 shows the PV generation for each zone at different penetration levels. The rooftop PV systems were integrated into 16 buses.

For each penetration level, I solved the power flow using the Matpower program. At each level, I inspected the voltage stability for all buses and the violation in the transmission lines. The following steps summarizes the first scenario:

1. Load the WECC model to mpc file.

2. Calculate the WECC total power demand.

3. Calculate the PV generation at (5%, 10%, 15%, 20%, 25%).

4. Calculate the PV generation for each zone.

5. Integrate the PV systems as a negative power demand.

6. Run the power flow and save the result in text formate.

7. Plot buses voltage and identify the violated lines by checking the complex power flow with its constraint.

8. End

3.2 Integration of Both Rooftop and Utility Scale PV Systems

The rooftop PV system produces only real power while the power system needs reactive power at high penetration levels to stabilize the system's voltage. Therefore, I created a second scenario that used two types of PV systems, including the rooftop PV systems and the utility scale PV systems. The utility scale PV systems are a large amount of PVs concentrated in a specific area and connected to the system through a step up transformer. The utility scale PV systems work at 0.9 power factor. The 0.9 power factor means 90% of the apparent power produced by the utility scale PV will be a real power. These new generation units had been added in each zone to PV buses at the transmission level (69kV). The rooftop PV systems' power generation remained at 5000 MW. The rooftop PV systems were integrated with the same buses that were used in the first scenario. The amount of power generation of utility scale PV systems vary depending on the penetration

Penetration Level / PV Type	5%	10%	15%	20%	25%
The rooftop PV systems	3039.3 MW	5000 MW	5000 MW	5000 MW	5000 MW
The utility scale PV systems	0 MW	1078.5 MW	4117.8 MW	7157 MW	10196 MW

Table 3.2: PV Generation at Different Penetration Levels

level. Table 3.2 shows the second scenario PV generation for each zone.

The following steps summarizes the second scenario:

1. Load the WECC model to mpc file.
2. Calculate the WECC total power demand.
3. Calculate the PV generation at (5%, 10%, 15%, 20%, 25%).
4. Calculate the PV generation for each type.
5. Integrate the PV systems as a negative power demand.
6. Run the power flow and save the result in text format.
7. Plot buses' voltage and identify the violated lines by checking the complex power flow with its constraint.
8. End

3.3 The Sensitivity

In this work we solve the power flow with Newton-Raphson method and we have the linearized form of the network.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \underbrace{\begin{bmatrix} \frac{\partial P}{\partial \Theta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \Theta} & \frac{\partial Q}{\partial V} \end{bmatrix}}_{\text{Jacobian}} \begin{bmatrix} \Delta \Theta \\ \Delta V \end{bmatrix} \tag{3.4}$$

The Jacobian's elements give the sensitivity between power flow and the bus voltages changes and that helps to avoid integrating PV systems into sensitive buses [20].

3.4 Load Voltage and PV Generation Relationship

The following work exemplifies the simplified system with PV generation source [13]. The goal is to find the relationship between the load voltage and PV generation. The steady state equations of the system represents the load voltage V_l in terms of the PV generation P_{PV} when solved (see Figure 3.1). S_g is the generator

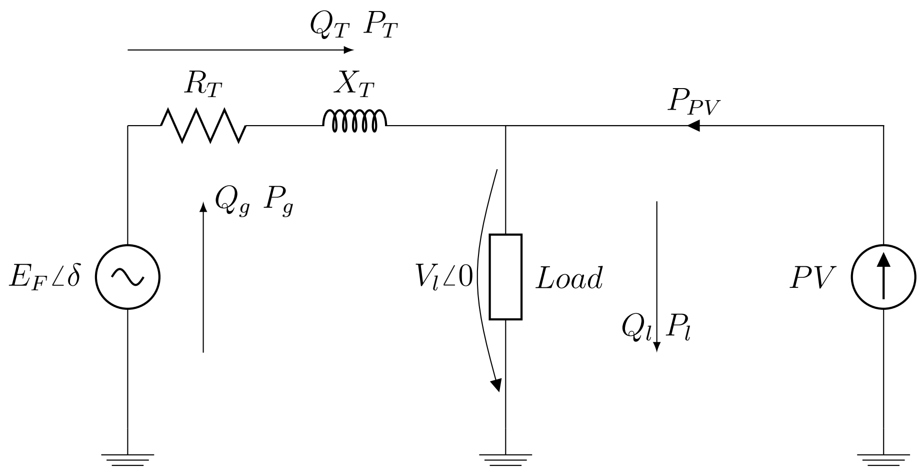

Figure 3.1: Two Bus Representation With PV System .

complex power and it consists of real part which is P_g and imaginary part Q_g.

$$\begin{aligned} S_g = (E_F\angle\delta)I^* &= [|E_F|cos\delta + jsin\delta]\left[\frac{E_F\angle\delta - V_l}{R_T + jX_T}\right]^* \\ &= \frac{R_TE_F^2 - R_TE_FV_lcos\delta + X_TE_FV_lsin\delta}{R_T^2 + X_T^2} \\ &+ j\frac{R_TE_FV_lsin(\delta) + X_TE_F^2 - X_TE_FV_lcos\delta}{R_T^2 + X_T^2} \end{aligned} \tag{3.5}$$

$$\begin{aligned} P_g &= Re\,[S_g] \\ &= \frac{R_TE_F^2 - R_TE_FV_lcos\delta + X_TE_FV_lsin\delta}{R_T^2 + X_T^2} \end{aligned} \tag{3.6}$$

$$\begin{aligned} Q_g &= Img\,[S_g] \\ &= \frac{R_TE_FV_lsin\delta + X_TE_F^2 - X_TE_FV_lcos\delta}{R_T^2 + X_T^2} \end{aligned} \tag{3.7}$$

In the following equations, S_T is the complex power flow in the transmission line and it consists of real part which is P_T and imaginary part Q_T.

$$\begin{aligned} S_T &= (V_T)I^* \\ &= [|E_F|cos(\delta) + jsin(\delta) - V_l]\Big[\frac{E_F\angle\delta - V_l}{R_T + jX_T}\Big]^* \\ &= \frac{R_T(|E_F|^2 - 2|E_F|V_l cos\delta + V_l^2}{R_T^2 + X_T^2} \\ &+ j\frac{X_T(|E_F|^2 - 2|E_F|V_l cos\delta + V_l^2}{R_T^2 + X_T^2} \end{aligned} \tag{3.8}$$

$$\begin{aligned} P_T &= Re\,[S_T] \\ &= \frac{R_T(|E_F|^2 - 2|E_F|V_l cos\delta + V_l^2}{R_T^2 + X_T^2} \end{aligned} \tag{3.9}$$

$$\begin{aligned} Q_T &= Img\,[S_T] \\ &= \frac{X_T(|E_F|^2 - 2|E_F|V_l cos\delta + V_l^2}{R_T^2 + X_T^2} \end{aligned} \tag{3.10}$$

The generator reactive power equal to the reactive power consumed by the transmission line added to the load reactive power.

$$\begin{gathered} Q_g = Q_T + Q_l \\ assumption : Q_l = kP_l \;\; where\; k\; is\; a\; constant \end{gathered} \tag{3.11}$$

The load real power equal to the real power delivered by PV system added to the generator real power minus the transmission line losses or consumptions.

$$P_l = P_{pv} + P_g - P_T \tag{3.12}$$

Combining (3.5),(3.6),(3.8) and(3.11) gives

$$V_l^4 + k^2 P_l^2 (R_T^2 + X_T^2) + (P_l - P_{PV})^2 (R_T^2 + X_T^2) + 2kP_l X_T V_l^2 + 2R_T V_l^2 - 2|E_F|^2 V_l^2 = 0 \tag{3.13}$$

Equation (3.13) demonstrates that the load voltage possesses quadratic characteristic in regards to PV generation.

Chapter 4: RESULTS

This chapter studies the steady state analysis for the simplified case of WECC. The chapter is divided into three sections: steady state stability for integrating only rooftop PV systems, steady state stability for integrating both rooftop PV systems and utility scale PV systems, and transmission lines violations. The first section states the principle findings for the first scenario where the system becomes unstable in light loaded buses at 15% and 25% penetration level. The second section discusses the enhancement after integrating both rooftop and utility scale PV systems. Finally, the third section displays the violation in the transmission lines for each scenario presented, explaining the causes of the results.

4.1 Steady State Stability for Integrating Only Rooftop PV Systems

Integrating large scale rooftop PV system causes instability in the steady state voltage of light loaded buses. The voltage simulation 4.1 shows the steady state voltages for all the buses. The voltage of light loaded buses has a quadratic behavior that may exceed the stability limits. The WECC system is divided into three zones and Figure 4.2 shows six buses from these zones. The result shows three different behaviors of the system's steady state voltage. The system follows quadratic behavior when the bus is lightly loaded or heavily loaded with PV integration at the bus. However, the heavily loaded buses that do not have any PV integration have a constant voltage with increase up to 15% penetration level. All bus voltage declines at 20% and 25% PV penetration levels.

4.1.1 The main findings

The voltage at the light loaded buses 27 and 136 increase with the increase of up to 15% the penetration level. However, the heavily loaded buses with PV integration, such as bus 7, have a peak value at 10% penetration level. The buses 52 and 161 serve as examples of heavy buses without any PV integration. Clearly, all buses decline after 15% penetration, but the decline rate for buses 27 and 136 is faster than other buses, suggesting the light loaded buses are sensitive to increased penetration levels, which indicate instability in these buses.

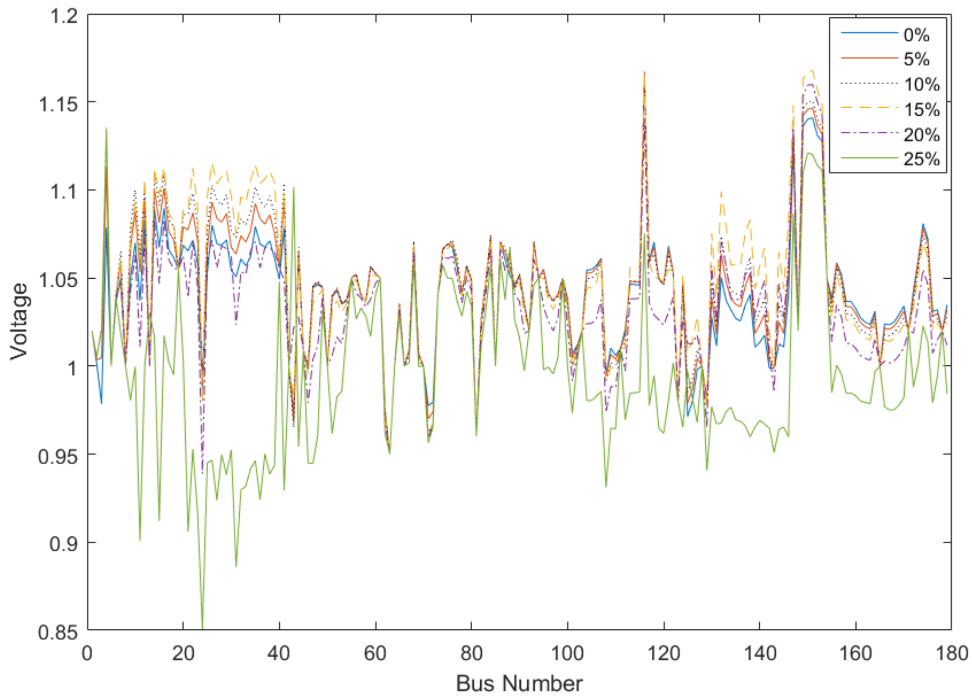

Figure 4.1: The Steady State System Voltages With Different Penetration Levels.

4.1.2 Explain the findings

Adding PV generation to the power grid augments the flow of the real power. The gradual growth in the real power flow interacts with the feeders' resistance and causes an increase in the buses' voltage [18] [19]. This voltage increase interestingly causes two phenomena. First, when voltage increases, the transmission lines produce reactive power proportional to the square of the voltage. Second, the transformers inject reactive power as the voltage increases. Formula 4.1 allows us

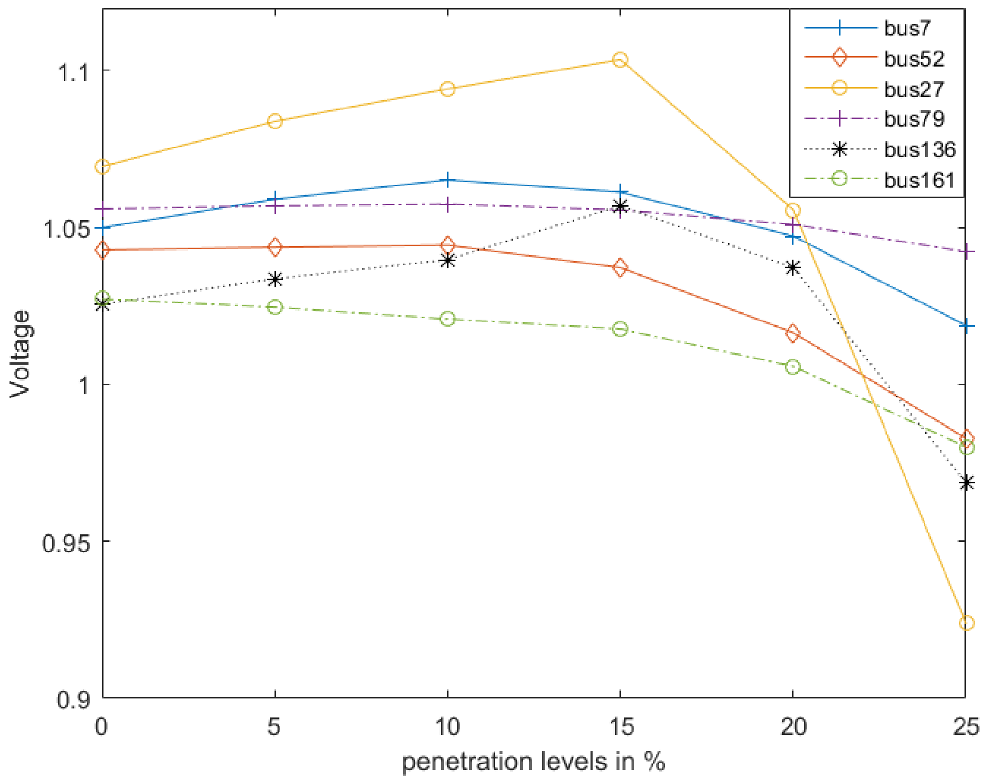

Figure 4.2: The Steady State System Voltages With Different Penetration Levels For Selected Buses.

to calculate the amount of reactive power produced by the transmission lines, explaining the relationship between the voltage increase and the transmission lines' reactive power production.

$$Transmission\ Line\ Productin = V^2 \times B \tag{4.1}$$

Figure 4.3 shows the injected reactive power by the transmission lines and the transformers. Thus, the results in Figures 4.2 and 4.3 prove the relation between the voltage and the reactive power injection. On one hand, both the steady state voltage and the reactive power injection increased up to 15% penetration level. On the other hand, the generated reactive power, reactive power losses, and the current flow decreased to a 15% penetration level. Because the transmission lines and the

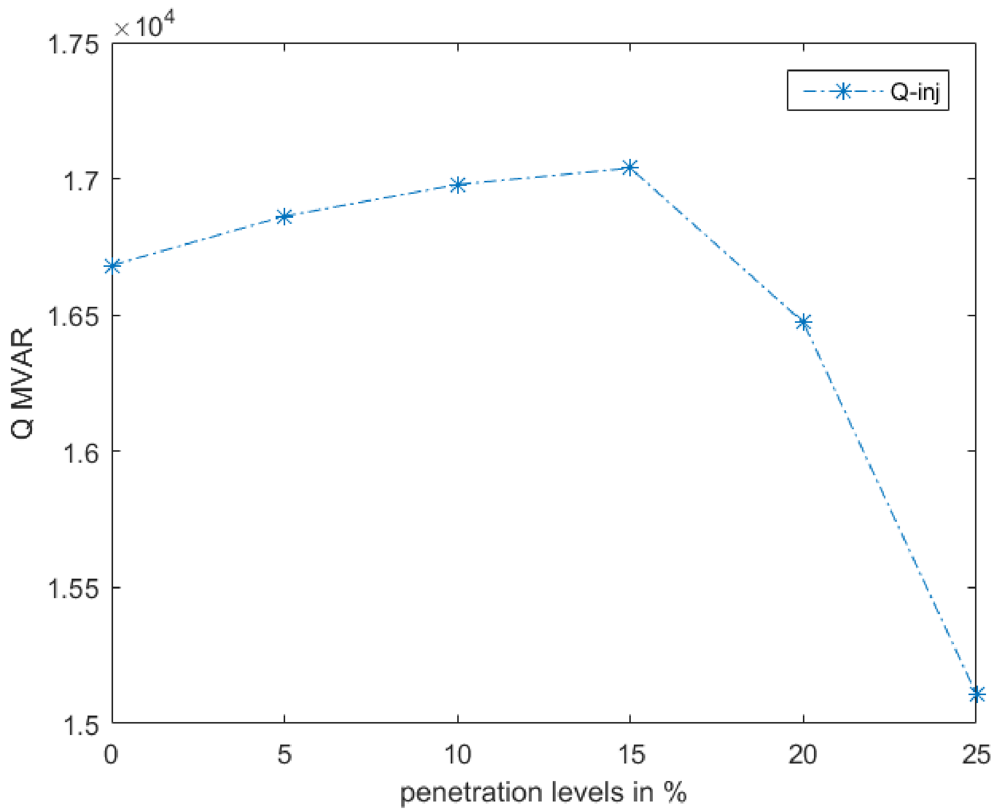

Figure 4.3: The Reactive Power Injected by Transmission Lines and Transformers.

transformers injected reactive power into the system, the generator decreased its reactive power production. Consequently, the apparent power flow in the system decreased which means the reactive power losses decreased.

However, when the PV penetration level exceeded 15%, the real power offset the power demand and began to revert to the transmission system. This reverted power led to an increase in the current flow in the system. This significant rise in the current caused an increase in the reactive power consumption by the transmission lines and transformers. Formula 4.2 demonstrates the cause and the effect relationship between the current flow and the transmission lines' reactive power consumption.

$$Transmission\ Line\ Consumption = I^2 \times X \tag{4.2}$$

The increase in the reactive power demand caused a considerable reduction in the voltage. As a result, the generators start producing more reactive power to meet the sudden increase in the reactive power demand [20]. Due to the additional reactive power flow through the system, the system's steady state voltage would experience an increased voltage drop [20]. This voltage reduction causes the system to become unstable. By comparing the two results in Figures 4.4 and 4.5, it is clear that the increase in the generated reactive power led to an increase in apparent power flow, current flow, and power losses. In contrast to these increases, the injected reactive power and the steady state voltage decreased dramatically.

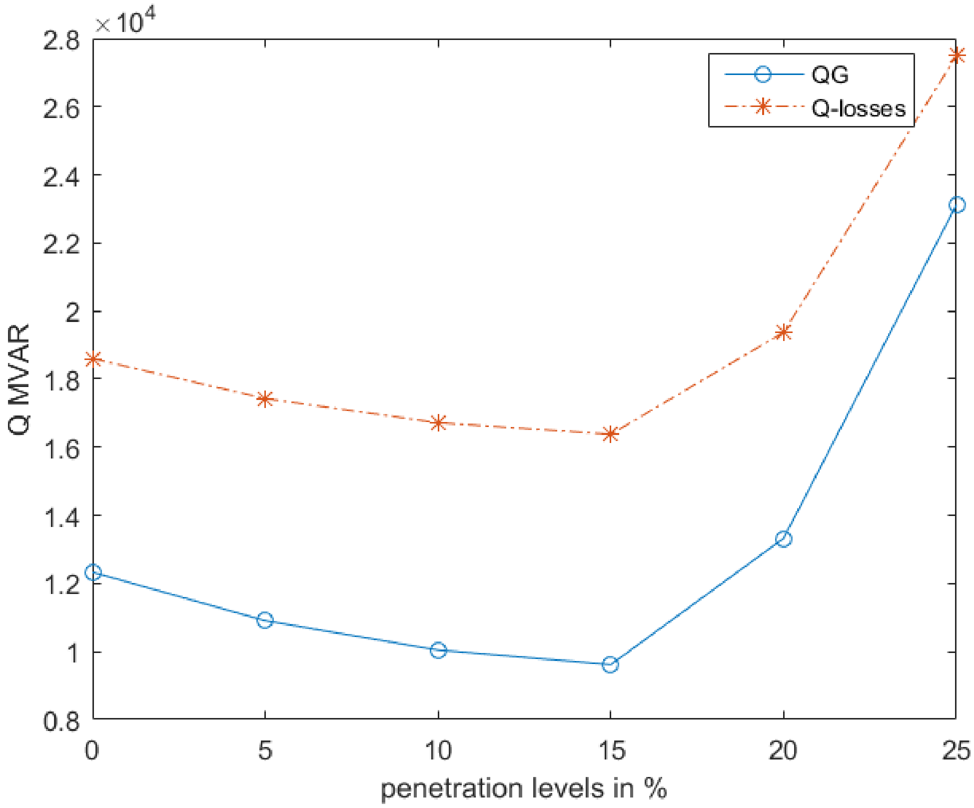

Figure 4.4: The Reactive Power Generated and The Reactive Power Losses.

Overall, integrating the large scale of the rooftop PV system that worked at unity power factor caused voltage instability in the light loaded buses.

4.2 Steady State Stability for Integrating Both Rooftop PV and Utility Scale PV Systems

Integrating both the utility scale PV systems and rooftop PV systems enhanced the system stability. The utility scale PV systems provided the system with reactive power. The simulation result in Figure 4.5 and 4.6 reflected that light loaded buses still have a quadratic behavior; however the system is stable. In the first

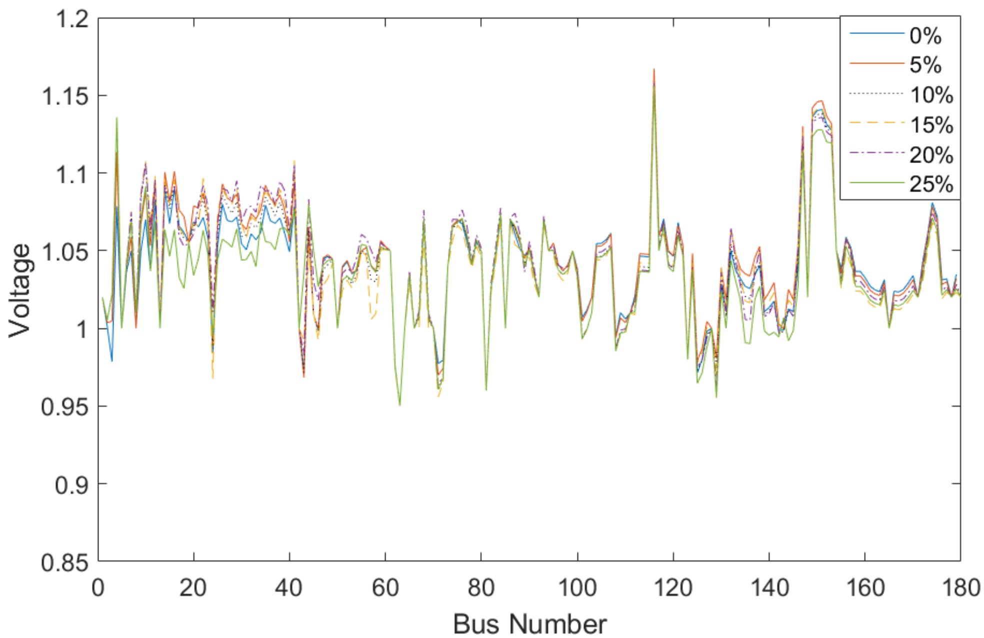

Figure 4.5: The Steady State System Voltages With Different Penetration Levels.

20% of penetration levels, the light loaded buses voltage increased by 2%. As the penetration level exceeded 20%, most of the buses' voltage declined, but much less

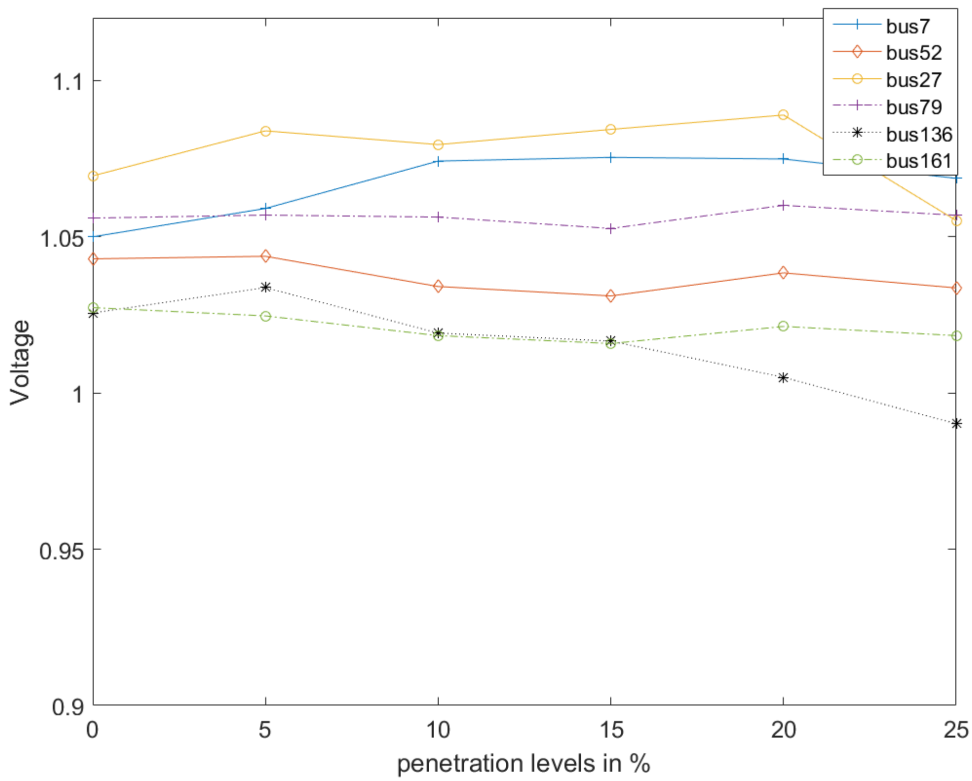

Figure 4.6: The Steady State System Voltages With Different Penetration Levels For Selected Buses.

significantly than witnessed in the first scenario. Also, the simulation result in Figures 4.7 and 4.8 showed the enhancement in the reactive power after using the utility scale PV systems. Using the utility scale PV systems reduced the reactive power losses. Also, they improved the injected reactive power at high penetration levels. In the first scenario, the injected reactive power dropped 2280 M-Var as the penetration level increased from 15% to 25%. However, in the second scenario,

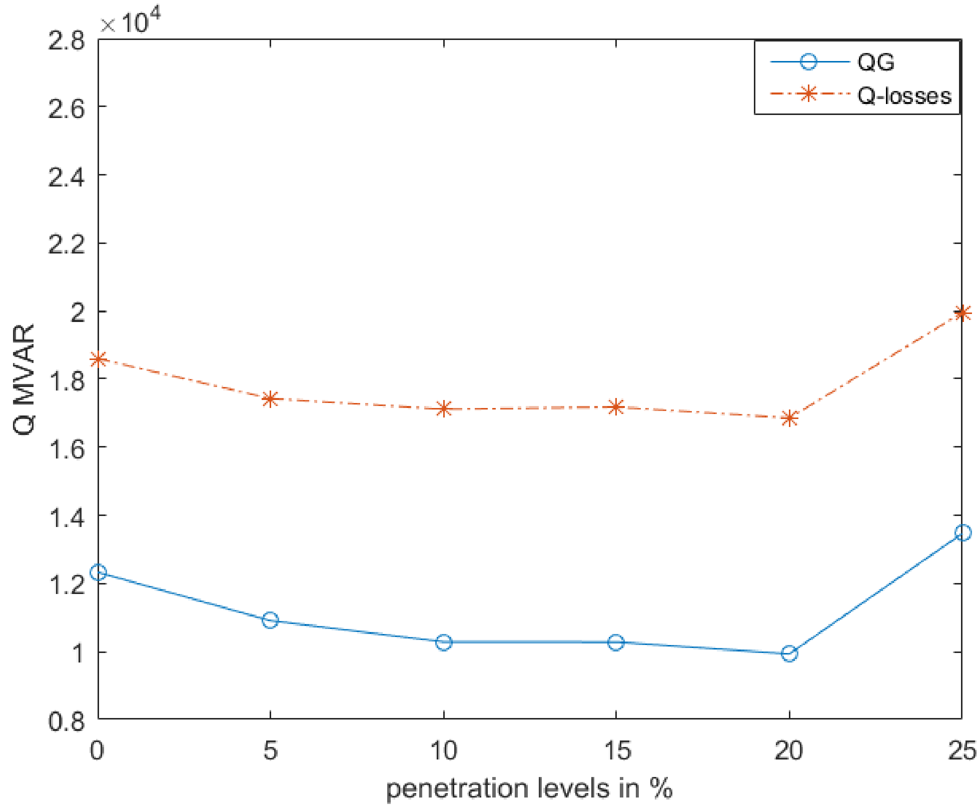

Figure 4.7: The Reactive Power Generated and The Reactive Power Losses.

the injected reactive power kept constant with slight increase at high penetration level.

4.3 Transmission Lines Violations

Based on the thesis results, integrating both rooftop and utility scale PV systems is preferable when integrating large scale PV systems. The rooftop only PV systems

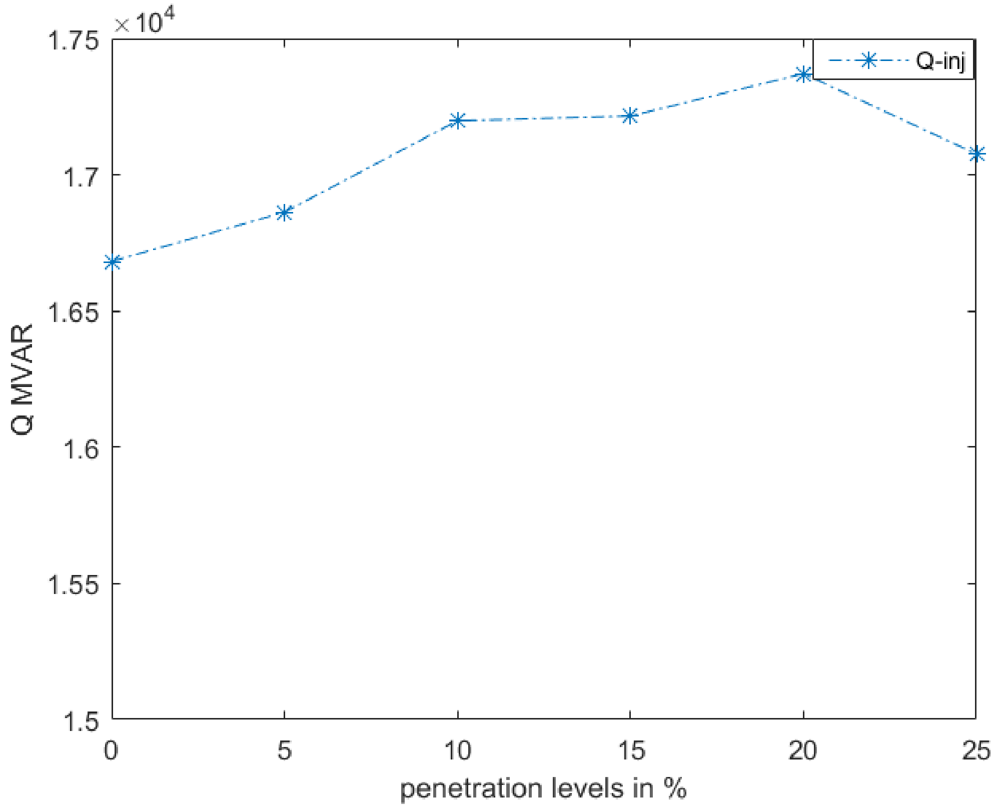

Figure 4.8: Injected Reactive Power.

have transmission line violations at high penetration levels. The number of the violated branches augments as the penetration level increases. These numbers indicate that integrating only rooftop systems cause more reverse power at high penetration levels than integrating both rooftop and utility scale PV systems. The increased reverse power in the transmission lines causes the flow current in the system to grow until it exceeds the transmission lines capability. Also, the generators increase the current flow by producing more reactive power at high

Penetration Levels / Scenario	5%	10%	15%	20%	25%
Rooftop Only PV systems	-	-	200	154,156,182,185,188,200	147,148,154,156,180,181,182,183,184,185,186,187,188,200
Both rooftop and utility scale PV systems	-	-	-	-	-

Table 4.1: Violated Branches

penetration levels to overcome the reactive power demand. This study verifies the complex power flow in the transmission lines because they have positive correlation with current flow. Table 4.1 shows the violated branches in each scenario. The second scenario does not have any violated lines because the utility scale PV system provided the system with a sufficient amount of reactive power at high penetration. Both scenarios do not have any transmission violation at 5% and 10% because the voltage increases which causes the current flow to decrease. Also, it indicates that there is no reverse power at these penetration levels and the load consumes the power of the PV systems. However, the power reverses at 15% in the first scenario, so branch 200 exceeds the constraint and the violated branches rise at 20% and 25% penetration level.

Chapter 5: Conclusion

The study was implemented to study the impact of increased penetration levels of PV systems on the voltage stability and the transmission lines. The study has explained the causes of the instability in the buses' voltage and has located the unstable buses. The goal of this study was to answer the following questions:

1. Does increased penetration of PV system affect the voltage stability?

2. Will the study locate any unstable buses?

3. Is it better to integrate only rooftop PV systems or both rooftop and utility scale PV systems? Why?

The study demonstrated that the increased penetration of rooftop only PV systems causes instability for the light loaded buses. The voltage of the light loaded buses has a quadratic behavior with increased penetration. These light loaded buses have an overvoltage at low penetration level due to the incremental increases in the real power. In contrast, at high penetration, the real power reverts to the transmission lines and the light loaded buses' voltage decreases dramatically.

Thus, their voltage exceeds the stability limits. The cause of this high reduction in the voltage is the sudden increase in the reactive power demand and the generator reactive power. However, this issue is overcome by integrating both rooftop and utility scale PV systems. Integrating both rooftop and utility scale PV systems enhances the system stability because the utility scale PV system provides the system by the reactive.

The key factor in voltage stability with increased penetration of PV systems is the amount of reactive power needed to stabilize the voltage. The future study will focus more on creating an optimization method for reactive power calculation as the penetration level of PV systems increases.

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APPENDICES

Appendix A: The Model

The case study simulated in this thesis is the simplified case of Western Electric Coordinating Council (WECC) [17]. The system consists of:

1. 179 bus, 29 machines, and 62-load bus.
2. Total system generation is 61411.43 MW.
3. Total system negative load is 7172.1 MW.
4. Total system load is 67957.51 MW.
5. Total loss is 626.02 MW.
6. The system has four voltage levels represented in (2 buses 138 kV, 37 buses 230 kV, 15 buses 345 kV, and 96 buses 500 kV).

Figure 1 shows a one-line diagram of the simplified WSCC 179-bus system.

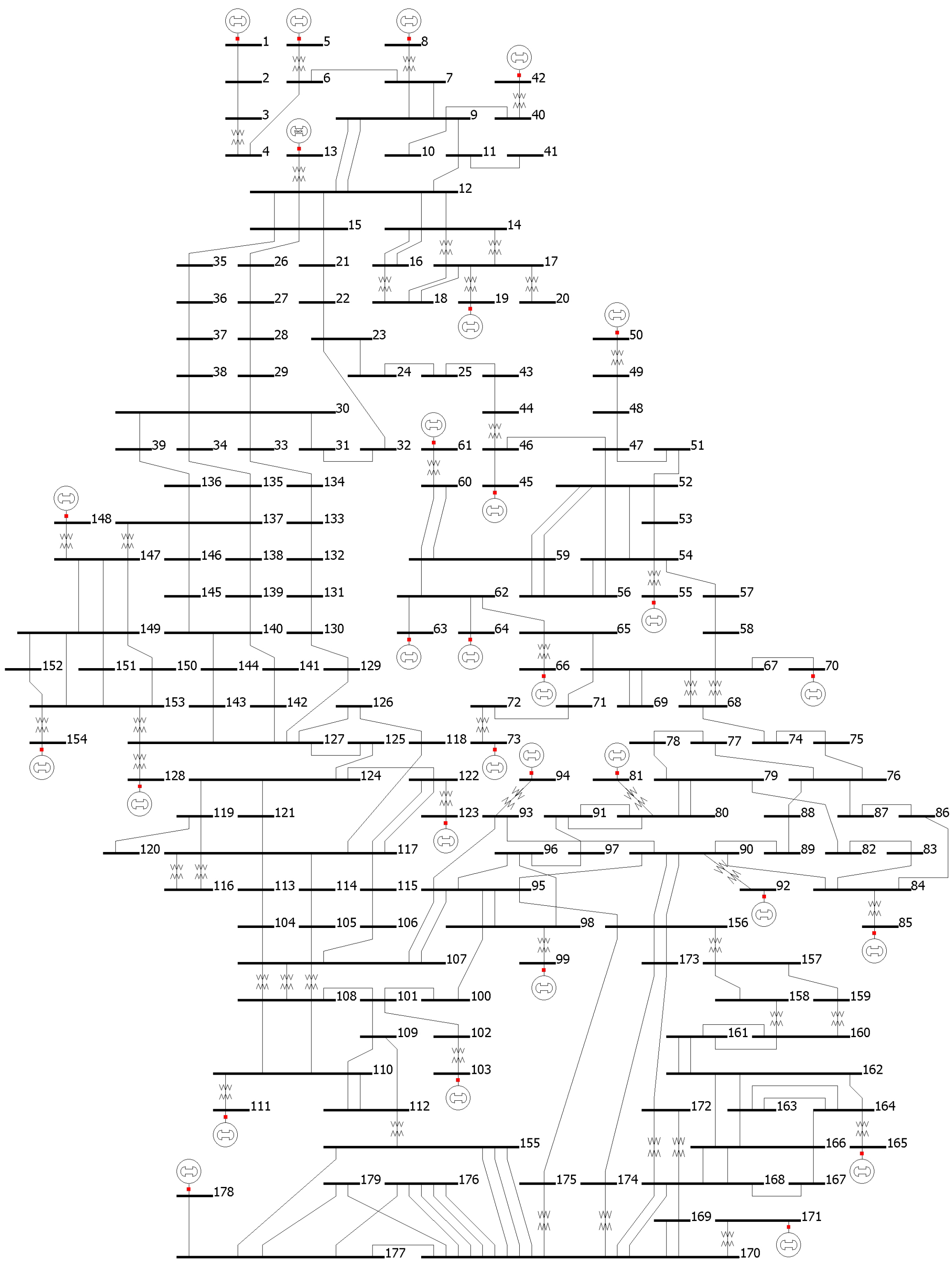

Figure A.1: The Simplified WSCC 179-bus System.