T.C.
Bahçeşehir University

ANALYSIS OF TRANSMISSION CONGESTION USING POWER-FLOW SOLUTIONS

Master's Thesis

Sıtkı GÜNER

İstanbul, 2009

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Prof. Dr. A. Bülent ÖZGÜLER
Director

This is to certify that we have read this thesis and that we find it fully adequate in scope, quality and content, as a thesis for the degree of Master of Science.

Examining Committee Members:

Asst. Prof. Dr. Bülent BİLİR (Supervisor) :

Prof. Dr. Emin TACER :

Assoc. Prof. Dr. Ayhan ALBOSTAN :

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ABSTRACT

ANALYSIS OF TRANSMISSION CONGESTION
USING POWER-FLOW SOLUTIONS
Güner, Sıtkı

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Transmission congestion has become a new challenge in an open-access environment of electric transmission networks. Transmission congestion is the inability of transmission lines to deliver power under some loading conditions. Congestion usually occurs when more power flows across the transmission lines than the scheduled rating of the lines. In today's world, electric power networks have been so much loaded that such a case has never been observed before. Due to overloading, transmission lines of the networks are congested. Management of transmission congestion is a crucial task for the successful operation of power systems. Our specific problem is to detect load centers or cities that are not congested for power transmission from a specific power plant such as newly-built wind farms and small size hydro dams.

Power generation from renewable energy sources has been increasing in the world. Therefore, electric power networks are grown up quickly. However, power transmission lines are not expanded as the same pace. When a new power plant is added to a power system, it may have positive or negative impacts, depending on where the new generator will be installed and what the new amount of its capacity will be. By analysis of transmission congestion, we assess the impacts of a new generator or generators added to the system because of energy demand.

In this research study, we use two power systems; one of which is the 20-bus IEEE system and the other is the 225-bus system of Istanbul Region. Our goal of this study is that how a power system is affected when a new generator is added to the system. As you may know, power system data are, in general, given in standard data formats such as IEEE Common Data Format and PTI (Power Technologies Incorporation) Data Format. To achieve what we promise for an extended power system with new additions, we first modify the power system data based on changes in demand, generation, and network. In order to do so, we add the new bus to the current network and increase the generation and demand. Subsequently, network and bus data are updated automatically. In this way, data become ready for running the power-flow program. Via this program, we reach the power-flow solutions. We code the power-flow program in MATLAB using Newton-Raphson method. Also note that the reactive power limits of generator buses are taken into account in the solutions. After obtaining the base case solution of the power flow, we select a candidate bus from load buses to apply incremental changes in real and reactive power. In order to assess the real and reactive power capacities of the candidate bus, we plot the P-V curve and the Q-V curve of the candidate bus using voltages versus real power P and voltages versus reactive power Q. As a result of this process, we have the real and reactive power capacities of the candidate bus and information about the congested parts of the power network. Therefore, we provide such information for power utilities to manage power efficiently and power marketers to sell power economically.

Deregulations of power systems have become very popular in many countries since energy resources are utilized efficiently without rigorous regulations. However, deregulations sometimes result in congestion problems. In the current deregulated environment of power systems, many countries have been faced with the congestion problem, which may lead to various other problems such as voltage instability, blackouts, and machine hunting. Under these circumstances, information about congestion is indispensable. Our study of power-flow solutions for various generation and loading conditions yields information to analyze congestion.

Keywords: Transmission Congestion, Power Flow, P-V Curve, Q-V Curve.

ÖZET

İLETİM TIKANIKLIĞININ GÜÇ-AKIŞ ÇÖZÜMLERİ İLE ANALİZİ

Güner, Sıtkı

Elektrik - Elektronik Mühendisliği

Tez Danışmanı: Dr. Bülent Bilir

Ağustos 2009, 54 sayfa

İletim tıkanıklığı, gelişen elektrik iletim şebekelerinde yeni bir rekabet alanı oluşturmaktadır. İletim tıkanıklığı, bazı yüklenme koşullarında elektrik hattında gücün iletilmemesidir. Bahsi geçen tıkanıklık, elektrik iletim hatlarının planlanandan daha fazla güç akışı olduğu zaman meydana gelir. Günümüzde, elektrik güç şebekeleri çok yüklenmektedir. Oysa aşırı yüklenme geçmişte sık rastlanan bir durum değildir. Hat tıkanıklığı yönetimi, güç sistemlerinin başarılı işletimi için çok önemli bir görevdir. Bu çalışmanın amacı, belirli bir güç santralinden güç iletimi yapılabilecek, hatları tıkanık olmayan, yük merkezleri veya şehirleri belirlemektir. Böyle bir santrale örnek olarak yeni kurulan rüzgâr çiftlikleri ve küçük ölçekli hidroelektrik barajları verilebilir.

Yenilenebilir enerjiden elde edilen elektrik üretimi her geçen gün artmaktadır. Bundan dolayı, elektrik şebekeleri hızlı bir şekilde büyümektedir. Buna karşın, iletim hatları aynı hızla gelişmemektedir. Yeni bir santralin kurulmasının konum ve üretim miktarına bağlı olarak elektrik şebekesine olumlu ve olumsuz etkileri vardır. İletim tıkanıklığı analizi ile sisteme eklenen yeni santralin güç sistemine etkileri incelenir.

Bu araştırmada, iki farklı güç sistemi kullanılmaktadır. Sistemlerden birisi 20 baralı IEEE sistemi; diğeri ise 225 baralı İstanbul Bölgesi'nin sistemidir. Bilindiği gibi, güç sistemi verileri genellikle IEEE veri formatı ve PTI veri formatı gibi standart

formatlarda verilir. İfade edilenlerin yapabilmesi için, ilk olarak yeni eklenecek baranın sistemin üretim, tüketim ve şebeke verilerinde yapacağı değişikliklerinin sistem verisine girişi yapılır, şebeke ve bara verileri otomatik olarak güncellenir. Böylece veri, güç-akış programını çalıştırmak için hazır duruma gelir. Bu program sayesinde güç-akış çözümlerine ulaşılır. Tezde geliştirilen güç-akış programında Newton-Raphson yöntemini kullanılır. Programın kodlaması MATLAB ortamında yapılır. Elde edilen güç-akış çözümlerinde jeneratörlerin reaktif güç limitleri dikkate alınmaktadır. Güç-akış çözümleri elde edildikten sonra, reel ve reaktif güçlerine belli bir oranda arttırmalar uygulanacak aday bara seçilir. Aday bara yük baraları arasından seçilir. Aday baranın reel ve reaktif güç kapasitesinin belirlenmesi için aday baranın P-V ve Q-V eğrileri çizdirilir. Bu işlemin sonucunda aday baraların reel ve reaktif güç limitlerine ve kullanılan elektrik şebekelerinin tıkanık kesimlerinin bilgisine ulaşılır. Bu sayede, elektrik sağlayıcılarının güç sistemini daha verimli yönetmeleri ve elektrik şirketlerinin elektriği daha ucuza satmaları için bilgi sağlanır.

Güç sistemlerinin deregulasyonları (serbestleştirme), birçok ülkede çok revaçta hale gelmektedir. Çünkü katı regülâsyonlarla (düzenleme) enerji kaynaklarından etkin şekilde yararlanılamamaktadır. Serbestleştirme kaynakların verimli kullanımı sağlarken iletim tıkanıklıklarına da sebep olmaktadır. Güç sistemlerinin günümüzdeki serbestleştirilmiş ortamında, birçok ülke gerilim kararsızlığı, ani elektrik kesintisi ve makine salınımı gibi sorunlara yol açan tıkanıklık sorunuyla karşı karşıya kalmaktadır. Bu şartlar altında, tıkanıklık hakkındaki bilgiler çok değerlidir.

Anahtar kelime: Hat Tıkanıklığı, Güç Akışı, P-V Eğrisi, Q-V Eğrisi.

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LIST OF ABBREVIATIONS

Active Power-Voltage	:	P-V
Institute of Electrical and Electronics Engineer	:	IEEE
Kirchhoff's Current Law	:	KCL
per unit	:	p.u.
Reactive Power-Voltage	:	Q-V
Türkiye Elektrik İşletmeleri Anonim Şirketi	:	TEİAŞ

LIST OF SYMBOLS

Admittance	:	Y
Current	:	I
Jacobian matrix	:	J
Reactive power	:	Q
Real power	:	P
Transformation ratio	:	1:a
Voltage magnitude	:	$\|V\|$
Voltage phase angle	:	δ

1. INTRODUCTION

1.1 BACKGROUND

Electric energy is the most popular form of energy, because it can be transported easily at high efficiency and reasonable cost than other form of energy. Power generation from renewable energy sources has been increasing in the world. Therefore, today's electric power networks are grown up quickly. However, power transmission lines are not expanded as the same pace. Therefore, power systems are operated more close to their maximum operation conditions. Under these circumstances, transmission congestion is frequently encountered problem in power systems. Transmission congestion occurs when the dispatch of transactions causes the violation on the transmission system. Transmission congestion may result from various reasons, such as transmission line outages, generator outages, changes in energy demand, and uncoordinated transaction. For the successful operation of power systems, management of transmission congestion is a crucial task for power engineers [Hussin, Hassan and Lo 2006].

In the electric power network, demand and supply must be balanced all the time in order to maintain the system frequency, voltage, and stability standards; Kirchhoff's laws and impedance of the whole network determine the power flows in the system. When there is congestion, generating capacity in congested area are relative scarcity, so congestion results in locational market power and causes invalidation of the optimization of generating resources in the whole network [He, Xu and Cheng 2004].

The power-flow problem is one of the most studied problems in power systems. Power flow is a problem in every step of the development of power transmission. The newly-added generators can cause the power-flow problem. Therefore, the power-flow solution has become a major step in power system planning and operation. The results of power-flow analysis are necessary for energy system planning, economic scheduling, and controlling.

A newly-added generator to a power system may have positive and negative impacts, depending on where the new generator will be installed and what the amount of its capacity will be [Kaymaz, Valenzuela and Park 2007]. This information is important for the power-utilities, power purchasers, and the grid operators. Because, any negative impact of the newly-added generator to the power system increases the energy cost and affects the power reliability and quality. When transmission constraints prevent delivery of energy from less expensive sources, energy that is deliverable from more expensive sources must be used instead. Because of transmission congestion, new cost is added the energy price. All impacts of the inability of transmission lines to deliver power have adverse impacts on electricity consumers [U.S. Department of Energy 2006].

1.2 LITERATURE REVIEW

The vast information about transmission congestion is given in report by the Department of Energy [US Department of Energy 2006]. The impacts of transmission congestion on market power in electricity market are described by the paper [He, Xu and Cheng 2004]. The paper by Kaymaz et. al. proposes the interaction between competition and transmission congestion on power generation expansion [Kaymaz, Valenzuela and Park 2007]. Feasibility evaluation and optimal dispatch model which are applied dispatch management, are dealed in [Wang et. al. 2000]. Analysis of transmission congestion using probabilistic reliability evaluation for KEPCO is discussed in [Tran et. al. 2006].

In this work, we study technical parts of the transmission congestion. However, economical impacts of transmission congestion are studied by many researchers. Some of the research works for the economical impacts of transmission congestion are given in [Hussin, Hassan and Lo 2006], [Raikar and Ilic 2001], [Fang and David 1999], and [Singh, Hao and Papalexopoulos 1998].

The fundamentals of power-flow analysis are covered well in [Saadat 2004], [Glover and Sarma 2001], and [Grainger and Stevenson 1994]. The reactive power limits of generators are considered in industrial application of power-flow solutions. A method of considering the reactive power limits of generators and their voltage adjustments, as a part of the power-flow solution using Newton-Raphson, is presented in [Mamandur and Berg 1982]. Current injection power-flow modeling for the solution of power-flow problems is proposed in [Costaa, Pereiraa and Martins 2001]. In [Alvarado 1999], it implements a power-flow solution with MATLAB environment of IEEE Power System Application Data Dictionary; power transfer distribution factors are also dealed in this paper. Power transfer distributions factors are important elements of the present congestion management strategies for operating in a deregulated environment.

The real and reactive power capacities are directly related to the system load margin. Determining the load margin is an important method to obtain real and reactive power capacities of the buses. Two of the most widely-used methods for the load margin are the determination of the real power margin P, which is associated with the P-V curve, and the determination of the reactive power margin Q, which is associated with the Q-V curve. In [Taylor 1994], broad information about the assessment of real and reactive power capacities is given. The paper by Chowdhury and Taylor proposes the Q-V curve power-flow method [Chowdhury and Taylor 2000]. Generator reactive power reserves (GRPR) related to voltage stability and voltage violations are investigated in [Leonardi and Ajjarapu 2008], [Randhawa et. al. 2008], and [Su et. al. 2006].

1.3 STATEMENT OF THE PROBLEM

Transmission congestion occurs when more power flows across the transmission lines than the scheduled rating of the lines. Management of transmission congestion is a crucial task for the successful operation of power systems. Our specific problem is to detect load centers or cities that are not congested for power transmission from a specific power plant such as a newly-built wind farms and small size hydro dams.

In this research study, we analyze the congestion using power-flow solutions for various load and generation levels. We detect the congested part of the power network such as some areas of the cities. We use two power systems; one of which is the 20-bus IEEE system and the other is the 225-bus system of Istanbul Region.

Our goal of this study is to analyze transmission congestion when a new generator is added to the power network. Under the condition that additional generation is supplied and the corresponding load is demanded, we run the power-flow program that we have developed. For various levels of generation and corresponding demand, we obtain power-flow solutions. In this way, we determine levels of generation and demand where congestion occurs. Therefore, our study provides information for electric utilities to operate the system effectively and power marketer to sell power economically.

1.4 METHODOLOGIES

In this research study, we analyze the congestion using power-flow solutions for various load and generation levels. Our goal is that how a power system is affected when a new generator bus is added the system. To achieve what we promise, we first modify the power system data. We can add the new buses and update the existing buses automatically. In this study, we write the codes for programs using MATLAB environment.

In order to obtain congested parts of a power networks, power-flow solutions play crucial role. The power-flow program is the major parts of our research study. The power flow is widely used in power system analysis. Power-flow solution predicts what the electrical state of the network will be when it is subject to a specified loading condition. The result of the power-flow is the voltage magnitude and the angle at each bus of the system. We develop a power-flow program as the tool for our analysis. Let us describe the power-flow problem. Consider an electric power system with n buses. There are four quantities for each bus. They are voltage magnitude $|V|$, phase angle δ, real power P, and reactive power Q. These n buses are consists of a single swing bus at which voltage magnitude $|V|$ and phase angle δ are specified, n_{pv} buses at which real power P and voltage magnitude $|V|$ are specified (these are PV buses), and n_{pq} buses at which real and reactive power (P, Q) are specified (these are PQ buses). The voltage angle of the swing bus serves as reference for the angles of the all other bus voltages. The PV buses are mostly generator buses at which the injected real power is specified. The PQ buses are primarily load buses. Evidently,

$$n = n_{pv} + n_{pq} + 1.$$

We need to calculate δ and Q at PV buses, $|V|$ and δ at PQ buses, and P and Q at the swing bus. In order to obtain these values, we solve the system of ($2n_{pv} + 2n_{pq} + 1 = 2n - 1$) power-flow equations using the node-voltage equation in the matrix form

$$I = YV,$$

where I is the bus injection-current vector, V is the bus voltage vector, and Y is the bus admittance matrix.

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\cos(\delta_i - \delta_j - \theta_{ij}) \quad (1.1)$$

$$Q_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\sin(\delta_i - \delta_j - \theta_{ij}) \quad (1.2)$$

As seen in equations (1.1) and (1.2), the power-flow problem is a nonlinear problem because of the sinusoidal terms and the product of voltage magnitudes. Therefore, we obtain numerical solutions using Newton-Raphson method. In our program, starting with initial guess with voltage magnitudes of 1.0 p.u and voltage angles of 0 degrees, we calculate the power-flow solution under the constraints of reactive power limits of generators with the tolerance of 0.001 p.u. For the two sample power systems, the 20-bus IEEE system and the 225-bus system of Istanbul Region, we run our power-flow program and obtain the solutions successfully.

We assess the real and reactive power limits via P-V and Q-V curves. P-V and Q-V curves can be readily calculated using power-flow program. As a result of this process, we have the real and reactive power limits of candidate buses and the congested parts of these power networks. We choose candidate buses from load buses to apply incremental changes in real power and reactive power. At each candidate bus, we start with the base case solution of the power-flow. In order to draw the P-V curve for a candidate bus, we increase real power by 0.75 p.u at each time and run the power-flow program successively until the power-flow does not converge. In this way, we have successive values of the real power P and the corresponding voltage magnitudes at the candidate bus. Using these values, the P-V curve is drawn for the real power and the voltage magnitude at the candidate bus. To draw the Q-V curve for a candidate bus, we apply the similar procedures as we perform to draw P-V curves.

2. POWER-FLOW ANALYSIS

2.1 INTRODUCTION

Power-flow analysis is a very important tool for all stage of energy system. The results of power-flow analysis are necessary for energy system planning, economic scheduling, and controlling. The principal information obtained from a power-flow study is the magnitude and phase angle of the voltage at each bus and the real and reactive power flowing in each line [Grainger and Stevenson 1994]. This chapter deals with the steady-state analysis of an interconnected power system during normal operation. The system is assumed to be operating under balanced three-phase steady-state conditions and the system is represented by a single-phase network. The network contains hundreds of buses and branches with impedances specified in per unit on a common MVA base [Saadat 2004].

A power system is consists of buses. There are three types of buses. These are swing bus, load bus, and generator bus. There are four quantities at each bus; they are voltage magnitude $|V|$, phase angle δ, real power P, and reactive power Q. The detail information about these buses as follows:

Swing bus: A bus is taken as a swing bus in each power system for power-flow solutions. At this bus, voltage magnitude and voltage angle are specified; real and reactive power are unknown. The voltage angle of the swing bus serves as reference for the angles of the all other bus voltages.

Load buses: At these buses, the active and reactive powers are specified; the voltage magnitude and voltage angle are unknown. Load buses are also called P-Q buses.

Generator buses: At these buses, the real power and the voltage magnitude are specified. The voltage angle and the reactive power are unknown. Generator buses are also called P-V buses.

Nodal or loop analysis is not suitable for power-flow studies, because the input data for loads are normally given in terms of power, not impedance. The power-flow problem is basically that of solving $2n$ nonlinear algebraic equations in $2n$ unknowns for an n bus power system. Therefore, its solution requires numerical analysis techniques. Many methods are used to solve these nonlinear equations, such as Gauss-Seidel, Newton-Raphson, and the decoupled version of Newton-Raphson (Fast Decoupled Power-Flow Solution). However, in power industry, Newton-Raphson is preferred, because it is more efficient and practical for power-flow solutions. In this respect, we have followed the preference in industry and have used Newton-Raphson method in our program.

In this chapter, the bus-admittance matrix is formulated; the Newton-Raphson method is explained; and it is employed in the solution of power-flow problems. Finally, we discuss the power-flow solutions by programs developed using MATLAB.

2.2 BUS-ADMITTANCE MATRIX

The bus-admittance matrix is extensively used for power system analysis. In order to obtain the node-voltage equations, consider the simple power system in shown in Figure 2.1. Since the nodal solution is based upon Kirchhoff's current law, impedances are converted to admittance; that is,

$$y_{ij} = \frac{1}{z_{ij}} = \frac{1}{r_{ij} + jx_{ij}}$$

(2.1)

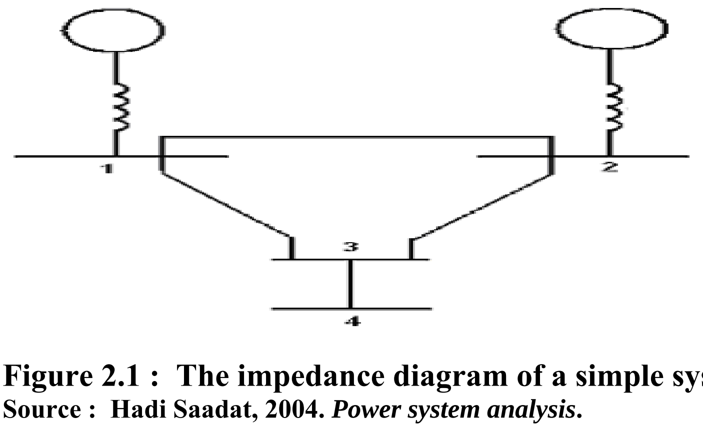

Figure 2.1 : The impedance diagram of a simple system
Source : Hadi Saadat, 2004. ***Power system analysis*****.**

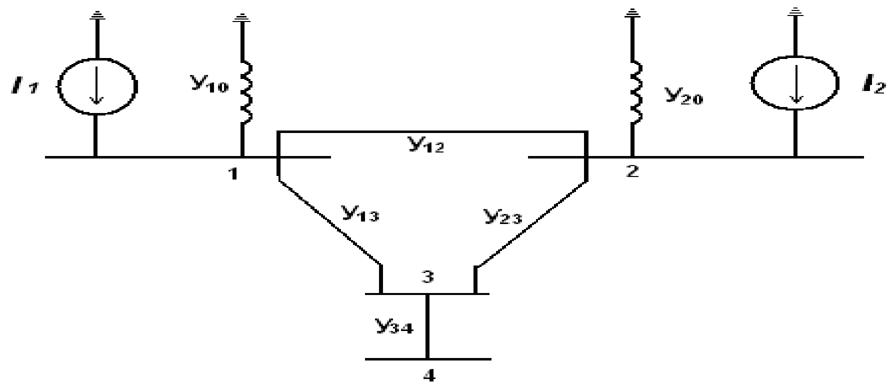

Figure 2.2 : The admittance diagram of the system in Figure 2.1
Source : Hadi Saadat, 2004. ***Power system analysis*.**

The circuit has been redrawn in Figure 2.2 in terms of admittances and transformation to current sources. Node 0 is taken as reference. Applying KCL to the independent nodes 1 through 4 results in

$$
\begin{aligned}
I_1 &= y_{10}V_1 + y_{12}(V_1 - V_2) + y_{13}(V_1 - V_3) \\
I_2 &= y_{20}V_2 + y_{12}(V_2 - V_1) + y_{23}(V_2 - V_3) \\
0 &= y_{23}(V_3 - V_2) + y_{13}(V_3 - V_1) + y_{34}(V_3 - V_4) \\
0 &= y_{34}(V_4 - V_3)
\end{aligned}
\tag{2.2}
$$

Rearranging these equations yields

$$
\begin{aligned}
I_1 &= (y_{10} + y_{12} + y_{13})V_1 - y_{12}V_2 - y_{13}V_3 \\
I_2 &= -y_{12}V_1 + (y_{20} + y_{12} + y_{23})V_2 - y_{23}V_3 \\
0 &= -y_{13}V_1 - y_{23}V_2 + (y_{13} + y_{23} + y_{34})V_3 - y_{34}V_4 \\
0 &= y_{34}V_4 - y_{34}V_3
\end{aligned}
\tag{2.3}
$$

We introduce the following admittances

$$
\begin{aligned}
Y_{11} &= y_{10} + y_{12} + y_{13} \\
Y_{22} &= y_{20} + y_{12} + y_{23} \\
Y_{33} &= y_{13} + y_{23} + y_{34} \\
Y_{44} &= y_{34} \\
Y_{12} &= Y_{21} = -y_{12} \\
Y_{13} &= Y_{31} = -y_{13} \\
Y_{23} &= Y_{32} = -y_{23} \\
Y_{34} &= Y_{43} = -y_{34}
\end{aligned}
$$

(2.4)

The node equation reduces to

$$
\begin{aligned}
I_1 &= Y_{11}V_1 + Y_{12}V_2 + Y_{13}V_3 + Y_{14}V_4 \\
I_2 &= Y_{21}V_1 + Y_{22}V_2 + Y_{23}V_3 + Y_{24}V \\
I_3 &= Y_{31}V_1 + Y_{32}V_2 + Y_{33}V_3 + Y_{34}V_4 \\
I_4 &= Y_{41}V_1 + Y_{42}V_2 + Y_{43}V_3 + Y_{44}V_4
\end{aligned} \tag{2.5}
$$

Extending the above relation to an n bus system, the node-voltage equation in matrix form is

$$
\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_i \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11}Y_{12}\cdots Y_{1i}\cdots Y_{1n} \\ Y_{21}Y_{22}\cdots Y_{2i}\cdots Y_{2n} \\ \vdots \\ Y_{i1}Y_{i2}\cdots Y_{ii}\cdots Y_{in} \\ \vdots \\ Y_{n1}Y_{n2}\cdots Y_{ni}\cdots Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_i \\ \vdots \\ V_n \end{bmatrix} \tag{2.6}
$$

or

$$
I_{bus} = Y_{bus}V_{bus} \tag{2.7}
$$

I_{bus} is the vector of the injected bus currents. The current is positive when flowing toward the bus and it is negative if flowing away from the bus. V_{bus} is the vector of bus voltages measured from the reference node. Ybus is known as the bus admittance matrix. The diagonal element of each node is the sum of admittances connected to it. It is known as the self-admittance [Saadat 2004].

$$
Y_{ii} = \sum_{j=0}^{n} y_{ij} \qquad j \neq i \tag{2.8}
$$

The off-diagonal element is equal to the negative of the admittance between the nodes. It is known as the mutual-admittance.

$$
Y_{ij} = Y_{ji} = -y_{ij}
$$

(2.9)

2.3 TAP CHANGING TRANSFORMERS

Transformers provide a small adjustment of voltage magnitude and shift the phase angle of the line voltage. Tap changing transformers and regulating transformers can be used to control the real and reactive power flows in a power system.

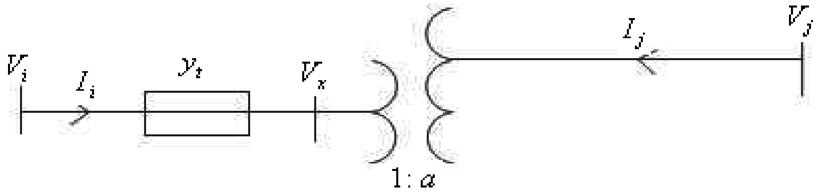

Figure 2.3 : Transformer with tap setting ratio a:1
Source : Hadi Saadat, 2004. *Power system analysis*.

Admittance y_t in per unit is the corresponding of the per unit impedance of the transformer which has the transformation ratio 1:a as shown in Figure 2.3. In the case of phase shifting transformers, a is a complex number. Consider a fictitious bus x between the turn ratio and admittance of the transformer. Since the complex power on either side of the ideal transformer is the same, it follows that if the voltage goes through a positive phase angle shift, the current will go through a negative phase angle shift [Saadat 2004], [Grainger and Stevenson 1994]. For the assumed direction of currents, we have

$$V_x = \frac{1}{a} V_j \qquad (2.10)$$

$$I_i = -a^* I_j$$

(2.11)

The current I_i can be expressed by

$$I_i = y_t (V_i - V_x)$$

(2.12)

Substituting for V_x, we have

$$I_i = y_t V_i - \frac{y_t}{a} V_j \qquad (2.13)$$

From 2.11, we have

$$I_j = -\frac{1}{a^*} I_i \tag{2.14}$$

Substituting for I_i from 2.13, we have

$$I_j = -\frac{y_t}{a^*} V_i + \frac{y_t}{|a|^2} V_j \tag{2.15}$$

Writing (2.13) and (2.15) in the matrix form results in

$$\begin{bmatrix} I_i \\ I_j \end{bmatrix} = \begin{bmatrix} y_t & -\frac{y_t}{a} \\ -\frac{y_t}{a^*} & \frac{y_t}{|a|^2} \end{bmatrix} \begin{bmatrix} V_i \\ V_j \end{bmatrix} \tag{2.16}$$

2.4 NEWTON-RAPHSON METHOD

Newton-Raphson method is the most used method for solving the nonlinear equation problems. The strategy behind the Newton-Raphson method is Taylor's series expansion and an initial estimate of the unknown. Let us consider the solution of the one-dimensional equation,

$$f(x) = c$$

(2.17)

If $x^{(0)}$ is an initial estimate of the solution, and $\Delta x^{(0)}$ is a small deviation from the correct solution, we must have

$$f\left(x^{(0)} + \Delta x^{(0)}\right) = c \tag{2.18}$$

Expanding the left-hand side of the above equation in Taylor's series about $x^{(0)}$ yield

$$f\left(x^{(0)}\right) + \left(\frac{df}{dx}\right)^0 \Delta x^{(0)} + \frac{1}{2!}\left(\frac{d^2 f}{dx^2}\right)^0 \left(\Delta x^{(0)}\right)^2 + \cdots = c$$

(2.19)

Assuming the error $\Delta x^{(0)}$ is very small, the higher-order terms can be neglected, which results in

$$\Delta c^{(0)} \cong \left(\frac{df}{dx}\right)^{0} \Delta x^{(0)} , \tag{2.20}$$

where

$$\Delta c^{(0)} = c - f\left(x^{(0)}\right). \tag{2.21}$$

Adding $\Delta x^{(0)}$ to the initial estimate will result in the second approximation

$$x^{(1)} = x^{(0)} + \frac{\Delta c^{(0)}}{(\frac{df}{dx})^{(0)}} \tag{2.22}$$

Use of this procedure yields the Newton-Raphson algorithm

$$\Delta c^{(k)} = c - f(x^{(k)}) \tag{2.23}$$

$$x^{(k+1)} = x^{(k)} + \Delta x^{(k)} \tag{2.24}$$

$$\Delta x^{(k)} = \frac{\Delta c^{(k)}}{(\frac{df}{dx})^{(k)}} . \tag{2.25}$$

The last equation can be rearranged as

$$\Delta c^{(k)} = J^{(k)} \Delta x^{(k)}, \tag{2.26}$$

where

$$J^{(k)} = \left(\frac{df}{dx}\right)^{k} \tag{2.27}$$

Now expand these expressions according to n-dimensional Taylor's series

$$\begin{bmatrix} c_1 - (f_1)^0 \\ c_2 - (f_2)^0 \\ \vdots \\ c_n - (f_n)^0 \end{bmatrix} = \begin{bmatrix} \left(\frac{\partial f_1}{\partial x_1}\right)^{(0)} \left(\frac{\partial f_1}{\partial x_2}\right)^{(0)} \cdots \left(\frac{\partial f_1}{\partial x_n}\right)^{(0)} \\ \left(\frac{\partial f_2}{\partial x_1}\right)^{(0)} \left(\frac{\partial f_2}{\partial x_2}\right)^{(0)} \cdots \left(\frac{\partial f_2}{\partial x_n}\right)^{(0)} \\ \vdots \\ \left(\frac{\partial f_n}{\partial x_1}\right)^{(0)} \left(\frac{\partial f_n}{\partial x_2}\right)^{(0)} \cdots \left(\frac{\partial f_n}{\partial x_n}\right)^{(0)} \end{bmatrix} \begin{bmatrix} \Delta x_1^{(0)} \\ \Delta x_2^{(0)} \\ \vdots \\ \Delta x_n^{(0)} \end{bmatrix}$$

Consequently, the Newton-Raphson algorithm for n-dimensional case becomes

$$X^{(k+1)} = X^{(k)} + \Delta X^{(k)} \tag{2.28}$$

$J^{(k)}$ is called the Jacobian matrix. Newton's method is mostly known method for finding better approximations to the roots of a function. The convergence of Newton's method is quadratic.

2.5 POWER-FLOW EQUATION

The power-flow is the computation of voltage magnitude and phase angle of each bus in a power system under balanced three-phase steady-state conditions. As a by-product of this calculation, real and reactive power flows in equipment such as transmission lines and transformers as well as equipment losses can be computed [Glover 2001].

As explained in before chapter, four quantities are associated with each bus and in general two quantities are known in each bus. Four quantities of each bus must be obtained for solution of power-flow problem.

Consider a typical bus of a power system network as shown Figure 2.4 application of the KCL to this bus results in

$$I_i = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_j \qquad j \neq i \tag{2.29}$$

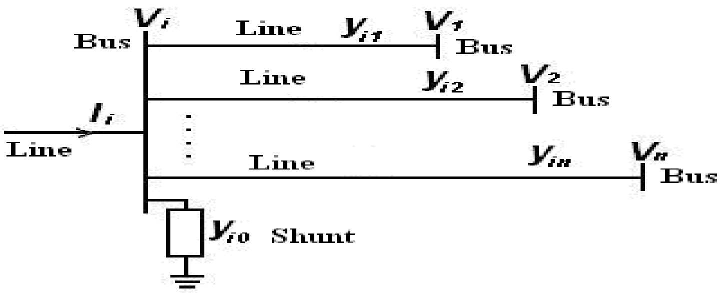

Figure 2.4 : A typical bus of the power-flow system
Source : Hadi Saadat, 2004. *Power system analysis*.

The real and reactive power at bus i is

$$P_i + jQ_i = V_i I_i^* \tag{2.30}$$

$$I_i = \frac{P_i - jQ_i}{V_i^*}$$

(2.31)

Substituting for I_i in (2.30)

$$\frac{P_i - jQ_i}{V_i^*} = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_j \qquad j \neq i \tag{2.32}$$

The above equation is the mathematical formulation of the power-flow problem results. This equation is a nonlinear equation, so it must be solved by iteration techniques [Saadat 2004].

2.6 NEWTON-RAPHSON FOR POWER-FLOW SOLUTION

The Newton-Raphson method is found to be more efficient and practical for large power systems. In this method, the number of iterations required to obtain a solution is independent of the system size, but more functional evaluations required at each iteration. In order to apply the Newton-Raphson method for the power-flow solution, bus voltages and line admittance is expressed in polar form. Equation (2.32) is separated the real and imaginary parts,

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos(\delta_i - \delta_j - \theta_{ij}) \tag{2.33}$$

$$Q_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin\left(\delta_i - \delta_j - \theta_{ij}\right) \tag{2.34}$$

These equations achieve a set of nonlinear algebraic equations in terms of the independent variables, voltage magnitude in per unit and phase angle in radians. If the Newton-Rahpson method is applied these equations,

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ --- \\ \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \left[\begin{array}{ccc|ccc} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\Delta\partial P_2^{(k)}}{\partial \delta_n} & \frac{\partial P_2^{(k)}}{\partial |V_2|} & \vdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} & \frac{\partial P_n^{(k)}}{\partial |V_2|} & \vdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \\ -- & -- & -- & -- & -- & -- \\ \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} & \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} & \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{array}\right] \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \partial_n^{(k)} \\ --- \\ \Delta \left|V_2^{(k)}\right| \\ \vdots \\ \Delta \left|V_n^{(k)}\right| \end{bmatrix}$$

In short form, the above equation can be written as,

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 J_2 \\ J_3 J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \tag{2.35}$$

For voltage- controlled buses, the voltage magnitudes are known. Therefore, if m buses of the system are voltage-controlled, m equations involving ΔQ and ΔV, the corresponding columns of the Jacobian matrix are eliminated. Accordingly, there are $n-1$ real power constraints and $n-1-m$ reactive power constraints, and the Jacobian matrix is of order $(2n-1-m)\times(2n-1-m)$. J_1 is of the order $(n-1)\times(n-1)$, J_2 is of the order $(n-1)\times(n-1-m)$, J_3 is of the order $(n-1-m)\times(n-1)$, and J_4 is of the order $(n-1-m)\times(n-1-m)$ [Saadat 2004]. At the end of a iteration, if a P-V bus violates the reactive power limit, the solution process must be changed. The reactive power at this violated bus is fixed at the limit and the bus type of this bus is changed as a PQ bus. That is voltage and reactive power of this bus exchange roles as knowns and unknowns. This change is executed until the reactive power at the bus is within limits. If a solution is reached, the voltage magnitude at this bus is returned the old value and also bus type of this bus is changed as a PV bus [Gross 1986].

The diagonal and off-diagonal elements of J_1 are

$$J_1(i,i) = \frac{\partial P_i}{\partial \delta_i} = -\sum_{j \neq i} |V_i||V_j||Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}) \tag{2.36}$$

$$J_1(i,j) = \frac{\partial P_i}{\partial \delta_j} = |V_i||V_j||Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}) \qquad j \neq i \tag{2.37}$$

The diagonal and off-diagonal elements of J_2 are

$$J_2(i,i) = \frac{\partial P_i}{\partial |V_i|} = 2|V_i||Y_{ii}| \cos(\theta_{ii}) + \sum_{j \neq i} |V_j||Y_{ij}| \cos(\delta_i - \delta_j - \theta_{ij}) \tag{2.38}$$

$$J_2(i,j) = \frac{\partial P_i}{\partial |V_j|} = |V_i||Y_{ij}| \cos(\delta_i - \delta_j - \theta_{ij}) \qquad j \neq i \tag{2.39}$$

The diagonal and off-diagonal elements of J_3 are

$$J_3(i,i) = \frac{\partial Q_i}{\partial \delta_i} = \sum_{j \neq i} |V_i||V_j||Y_{ij}| \cos(\delta_i - \delta_j - \theta_{ij})$$

(2.40)

$$J_3(i,j) = \frac{\partial Q_i}{\partial \delta_j} = -|V_i||V_j||Y_{ij}| \cos(\delta_i - \delta_j - \theta_{ij}) \qquad j \neq i \tag{2.41}$$

The diagonal and off-diagonal elements of J_4 are

$$J_4(i,i) = \frac{\partial Q_i}{\partial |V_i|} = -2|V_i||Y_{ii}| \sin(-\theta_{ii}) + \sum_{j \neq i} |V_j||Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}) \tag{2.42}$$

$$J_4(i,j) = \frac{\partial Q_i}{\partial |V_j|} = |V_i||Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}) \qquad j \neq i \tag{2.43}$$

$\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are

$$\Delta P_i^{(k)} = P_i^{(sch)} - P_i^{(k)} \tag{2.44}$$

$$\Delta Q_i^{(k)} = Q_i^{(sch)} - Q_i^{(k)} \tag{2.45}$$

The new estimates for bus voltages are

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \tag{2.46}$$

$$\left|V_i^{(k+1)}\right| = \left|V_i^{(k)}\right| + \Delta\left|V_i^{(k)}\right| \tag{2.47}$$

The procedure for power-flow solution by the Newton-Raphson method is as follows:

1. Read system and load data.
2. Y_{bus} is constituted.
3. Initialize δ , V
4. Calculate ΔP and ΔQ .
5. Calculate Jacobian matrix (2.36 through 2.43).
6. Solve for the voltage angle and magnitude (2.46 and 2.47).
7. Update the voltage magnitude and angles.
8. Check the stopping conditions. If met then terminate, else go to step 3.

$$\begin{aligned} \left|\Delta P_i^{(k)}\right| &\le \varepsilon \\ \left|\Delta Q_i^{(k)}\right| &\le \varepsilon \end{aligned} \tag{2.48}$$

2.7 LINE FLOW AND LOSSES

After computation of the voltage magnitude and voltage angle at each bus, the next step is the calculation of line flows and losses. Consider the line connecting the two buses i and j in Figure 2.5.

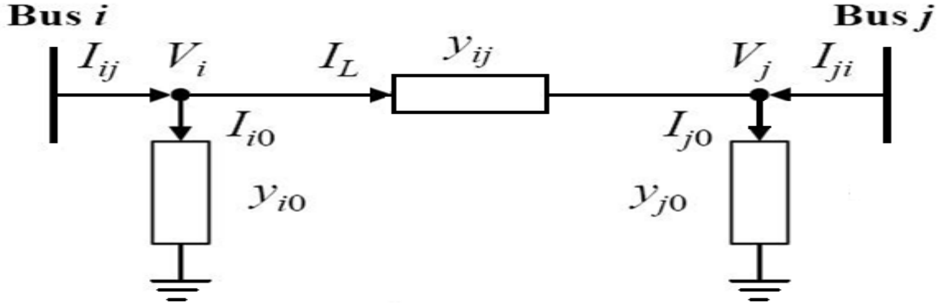

Figure 2.5 : Transmission line model for calculating line flows
Source : Hadi Saadat, 2004. *Power system analysis*.

The line current I_{ij},

$$I_{ij} = I_L + I_{i0} = y_{ij}(V_i - V_j) + y_{i0}V_i \qquad (2.49)$$

The line current I_{ji},

$$I_{ji} = -I_L + I_{j0} = y_{ij}(V_j - V_i) + y_{j0}V_j \qquad (2.50)$$

The complex powers S_{ij} and S_{ji},

$$S_{ij} = V_i I^*_{ij} \qquad (2.51)$$

$$S_{ji} = V_j I^*_{ji} \qquad (2.52)$$

The power loss in line $i \rightarrow j$ is the algebraic sum of the power-flows determined from (2.51 and 2.52)

$$S_{loss_{ij}} = S_{ij} + S_{ji} \qquad (2.53)$$

2.8 POWER-FLOW PROGRAM

The power-flow computer program is the major tool for analyzing transmission congestion. This program computes all unknown parameters at each bus in a power system. Real power and reactive power flows for all components interconnecting the buses, as well as line losses, are also computed. Both existing power system and proposed changes including new generation and transmission to meet projected load growth are of interest [Glover and Sarma 1994] .

Conventional nodal or loop analysis is not suitable for power-flow studies, because the loads are known as complex powers, not impedances; also generators are considered as power sources, not voltage or current sources. The power-flow problem is therefore formulated as a set of nonlinear algebraic equations suitable for computer solutions [Gross 1986], [Glover and Sarma 1994].

In previous sections, we overview all steps of the solution of power-flow problem using Newton- Rapson methods. All power-flow equations and input/output data are given in per-unit. We discuss the power-flow problem and its solutions by programs developed using MATLAB.

The main program of power-flow solutions is **pwr_flw**. This program calls the other programs; Modifying the power system is **addfun**, bus admittance matrix is **ybus**, Newton- Raphson method is **pfnewton**. The program plotting P-V curve is named as **nose_P** and the program **nose_Q** plots Q-V curve.

pwr_flw: This program is main program for the power-flow solution. The power system data must be getting IEEE Common Data Format. The power system data is converted to matrix form. Then, data modifying program is called to add a new bus or update the existing buses. Bus-admittance matrix is constituted. Subsequently, Jacobian matrix is constructed and the voltage magnitude and the angle at each bus is solved using Newton-Raphson method. Reactive powers of generator buses and real and reactive powers of swing bus are calculated using newly-obtained voltages. If reactive power of a generator bus is not within limits, the solution process is changed. The reactive power at this violated bus is fixed at the limit and the bus type of this bus is changed as a PQ bus. This change is executed until the reactive power at the bus is within limits. When all unknowns are solved within the constrains, power-flow solution has been obtained. The results of power-flow solution are used for plotting P-V and Q-V curves of candidate bus. The flowchart of power-flow program is shown in Figure 2.6. You can find the program **pwr_flw** in APPENDIX A1.

addfun: This program modifies the power system data. A new bus can be added or a existing bus can be updated using this program. You can find the program **addfun** in APPENDIX A2.

ybus: This program requires the line and transformer parameters and transformer tap settings specified. It converts impedance to admittance and obtain the bus admittance matrix. You can find the program **ybus** in APPENDIX A3.

pfnewton: This program obtains the power-flow solution using Newton-Raphson method. This program computes the voltage magnitude and voltage angle at each bus in a power system. In this program, firstly Jacobian matrix is constructed and power mismatches are calculated. Then, the voltage magnitudes and angles are computed and newly-obtained voltage magnitudes and angles are updated. The tolerance is checked. If the maximum power mismatch is bigger than the tolerance, Jacobian matrix is constructed again using newly-obtained voltage magnitudes and angles. This process is run until to reach the convergence. Then, if a P-V bus violates the reactive power limit, this program calls the program **Qlim**. At the end of the program **Qlim**, the tolerance is checked again. This program runs until to reach the convergence. The flowchart for Newton-Raphson algorithm is shown in Figure 2.7. You can find these programs in APPENDIX A4.

printout: This program produces the numerical result of the power-flow solution of the power system in a tabulated form. This result includes the voltage magnitude and voltage angle, real and reactive power of generator and loads. It reveals the active and reactive power-flow entering the line terminals and line losses as well as the net power at each bus. The total real and reactive power losses is also listed. You can find the program **printout** in APPENDIX A5.

nose_P and nose_Q : This program is used for to obtain the real and reactive power limits of the candidate bus. It plots P-V and Q-V curves of the candidate bus. Firstly, a candidate bus is selected to plot P-V and Q-V curves. Then, the power-flow program is run. At the end of power-flow program, the convergence is checked. If the convergence is reach, the P, Q, and V values of the candidate bus at this iteration is kept. If not, P-V and Q-V curves of the candidate bus are plotted. The flowchart for plotting P-V and Q-V curves is shown in Figure 2.8. You can find the programs, **nose_P** and **nose_Q** in APPENDIX A6.

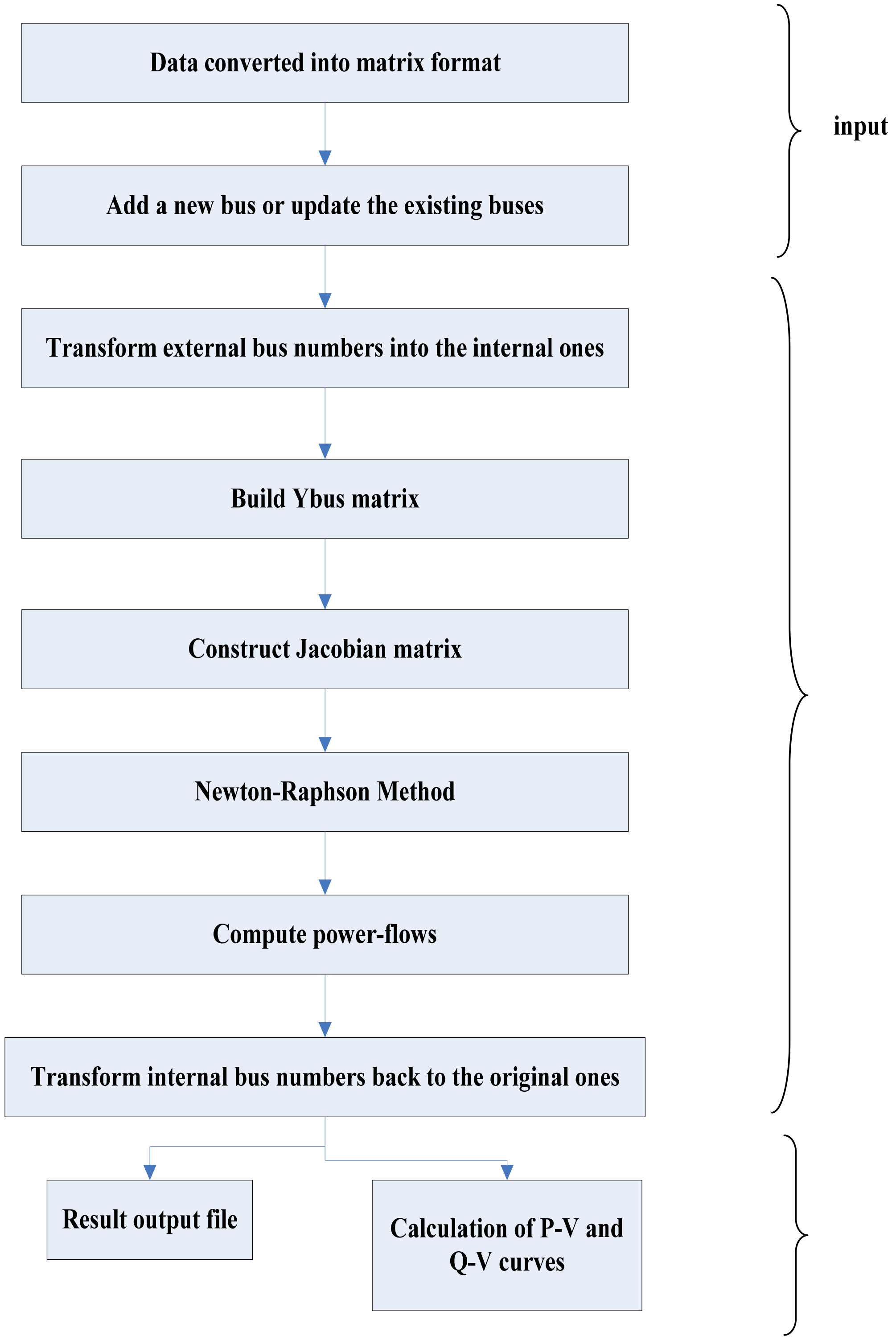

Figure 2.6: Flowchart for power-flow program

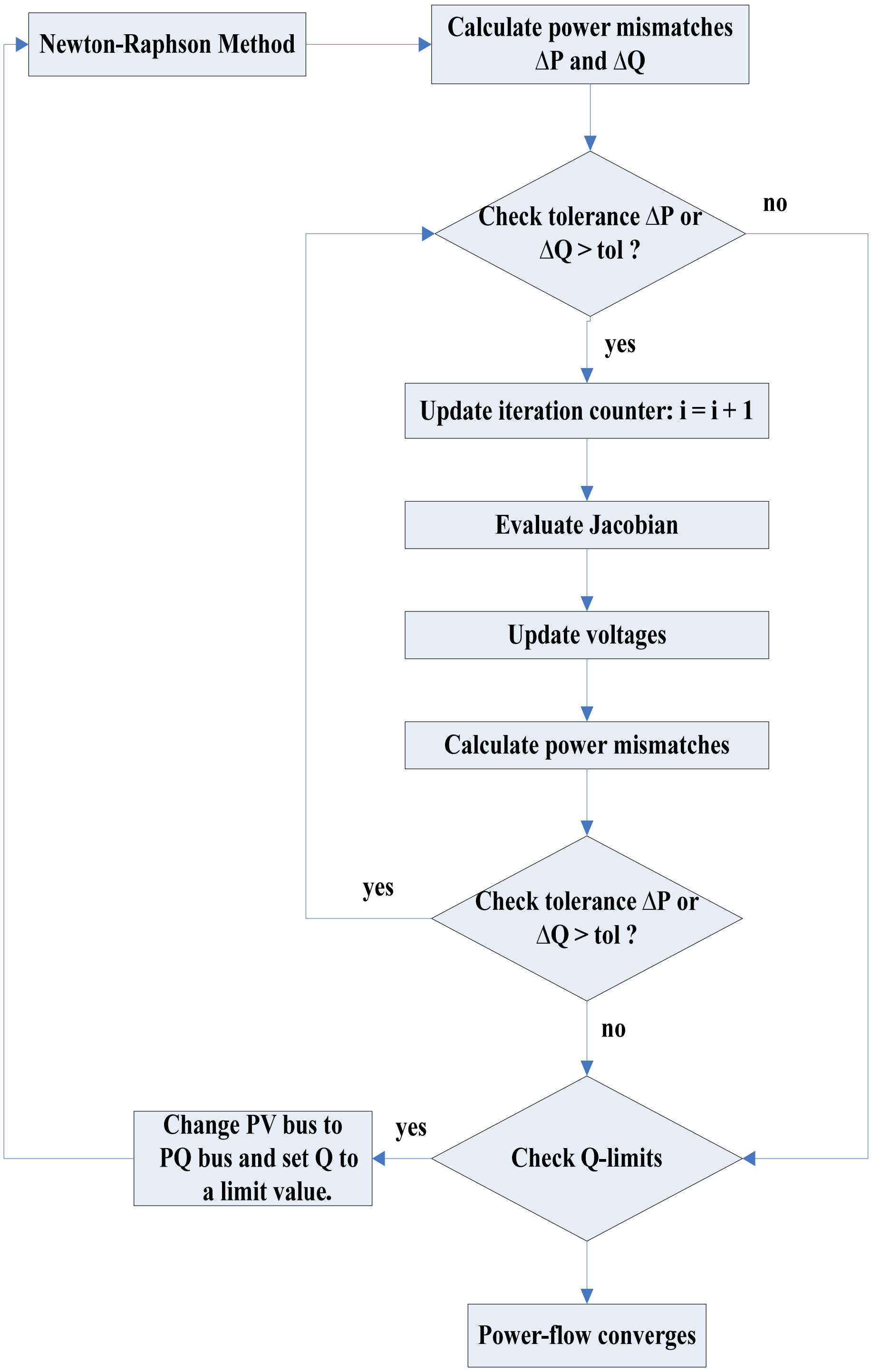

Figure 2.7: Flowchart for Newton-Raphson algorithm

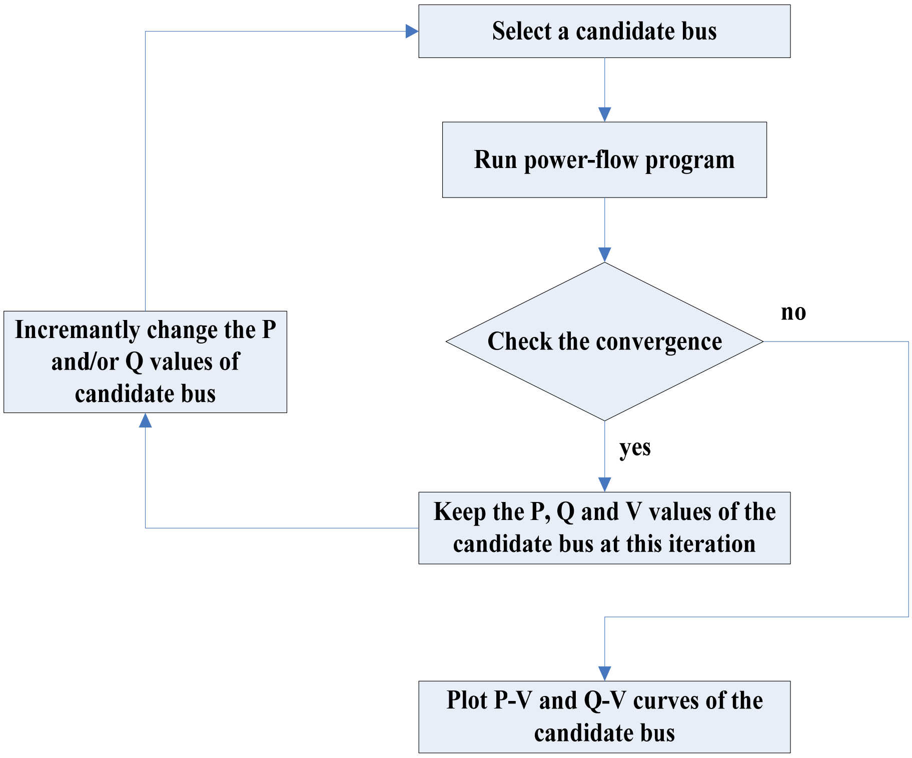

Figure 2.8: Flowchart for plotting P-V and Q-V curves

3. ASSESSMENT OF REAL AND REACTIVE POWER CAPACITIES USING P-V AND Q-V CURVES

3.1 INTRODUCTION

The methods of P-V and Q-V curves are mostly used for voltage stability analysis. Transmission congestion is directly related to voltage stability. Therefore, we deal with P-V and Q-V curves for assessment of the real and reactive power limits of the candidate bus. The methods of P-V and Q-V curves are widely accepted tools; they can provide real and reactive power margins. Power marketers need to P_V and Q-V curves of candidate bus to get information of the maximum transferable power to this bus. P-V and Q-V curves are generated by series of power-flow solutions.

In this chapter, we describe P-V and Q-V curves; explain how to compute real and reactive power margin; and discuss research methodology that we follow for assessment of real and reactive power capacities of candidate bus. We also present our results with P-V and Q-V curves for various load buses of the 20-bus IEEE system and the 225-bus system of Istanbul Region.

3.2 ASSESSMENT OF REAL POWER CAPACITY USING P-V CURVES

In order to obtain the maximum transferable real power, the relationship between transmitted P and receiving end V is of interest. The P-V curves, real power- voltage curve, are used to determine the MW distance from the operating point to the critical voltage. A typical P-V curve is shown in Figure 3.1. Consider a single, constant power load connected through a transmission line to an infinite-bus. Let us consider the solution to the power-flow equations, where P, the real power of the load, is taken as a parameter that is slowly varied, and V is the voltage of the load bus. The three regions shown in Figure 3.1 are related to the parameter P. In the first region, the power-flow has two distinct solutions for each choice of P; one is the desired stable voltage and the other is the unstable voltage. As P is increased, the system enters the second region, where the two solutions intersect to form one solution for P, which is the maximum. If P is further increased, the power-flow equations fail to have a solution. This process can be viewed as a bifurcation of the power-flow problem. The method of maximum power transfer determines critical limits on the load bus voltages, above which the system maintains steady-state operation.

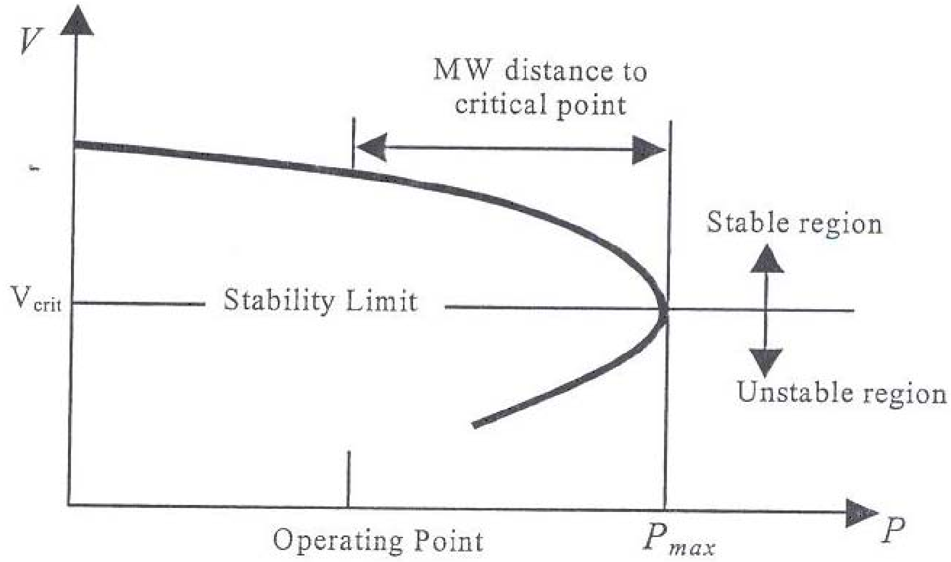

Figure 3.1: Real power-voltage (P-V) curve
Source: Prabha Kundur, 1994. *Power system stability and control.*

The P-V curve is drawn for the load bus and the maximum transferable power is calculated. Each value of the transferable power corresponds to a value of the voltage at the bus until $V = V_{crit}$ after which further increase in power results in deterioration of bus voltage. The top portion of the curve is acceptable operation whereas the bottom half is considered to be the worsening operation. The risk of voltage collapse is much lower if the bus voltage is further away, by an upper value, from the critical voltage corresponding to P_{max}. Hence, the P-V curve can be used to determine the system's critical operating voltage and collapse margin [Kundur 1994].

3.2 ASSESSMENT OF REACTIVE POWER CAPACITY USING Q-V CURVES

The Q-V curves are used to determine the Mvar distance from the operating point to the critical voltage. A typical Q-V curve is shown in Figure 3.2. It shows the sensitivity and variation of bus voltages with respect to reactive power injections or absorptions. Scheduling reactive loads rather than voltage produces Q-V curves. These curves are a more general method of assessing reactive power limit of a critical bus.

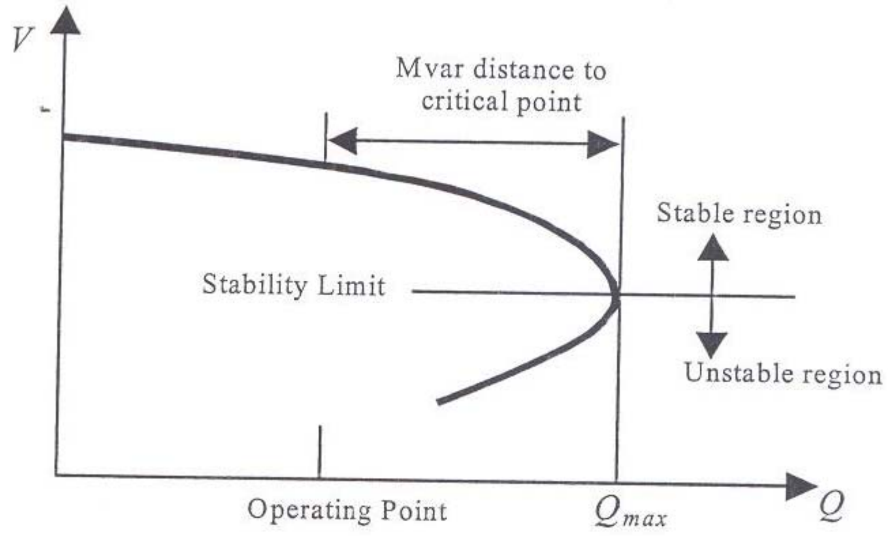

Figure 3.2: Reactive power-voltage (Q-V) curve
Source: Prabha Kundur, 1994. *Power system stability and control.*

If voltage level exceeds the limit, reactive support is installed to improve voltage profiles. With such an action, voltage level can be maintained within acceptable limits under a wide range of MW loadings. In reality, voltage level may never decline below that limit as the system approaches its steady-state stability limits.

In Figure 3.2, the Q axis shows the reactive power that needs to be added or removed from the bus to maintain a given voltage at a given load. The reactive power margin is the Mvar distance from the operating point to the bottom of the curve. Near the nose of a Q-V curve, sensitivities get very large and then reverse sign. Also, it can be seen that the curve shows two possible values of voltage for the same value of power. The power system operated at lower voltage value would require very high current to produce the power. That is why the bottom portion of the curve is classified as an unstable region; the system cannot be operated, in steady state, in this region. The top portion of the curve represents the stability region while the bottom portion from the stability limit indicates the unstable operating region. It is preferred to keep the operating point far from the stability limit [Kundur 1994].

3.3 RESEARCH METHODOLOGY OF ASSESSMENT OF REAL AND REACTIVE POWER CAPACITIES

In this research study, we analyze the congestion using power-flow solutions for various load and generation levels. We detect the congested part of the power network such as some areas of the cities. We use two power systems; one of which is the 20-bus IEEE system and the other is the 225-bus system of Istanbul Region which is a real power system of which data are provided us by TEİAŞ. The one-line diagram of this system is given in Figure 3.3. In order to analyze transmission congestion when a new generator is added the power network, firstly we should have a program that modifies the power system data automatically. We code this program in MATLAB environment as all programs we code in this study. Adding a new bus or updating the existing buses can be done using this program.

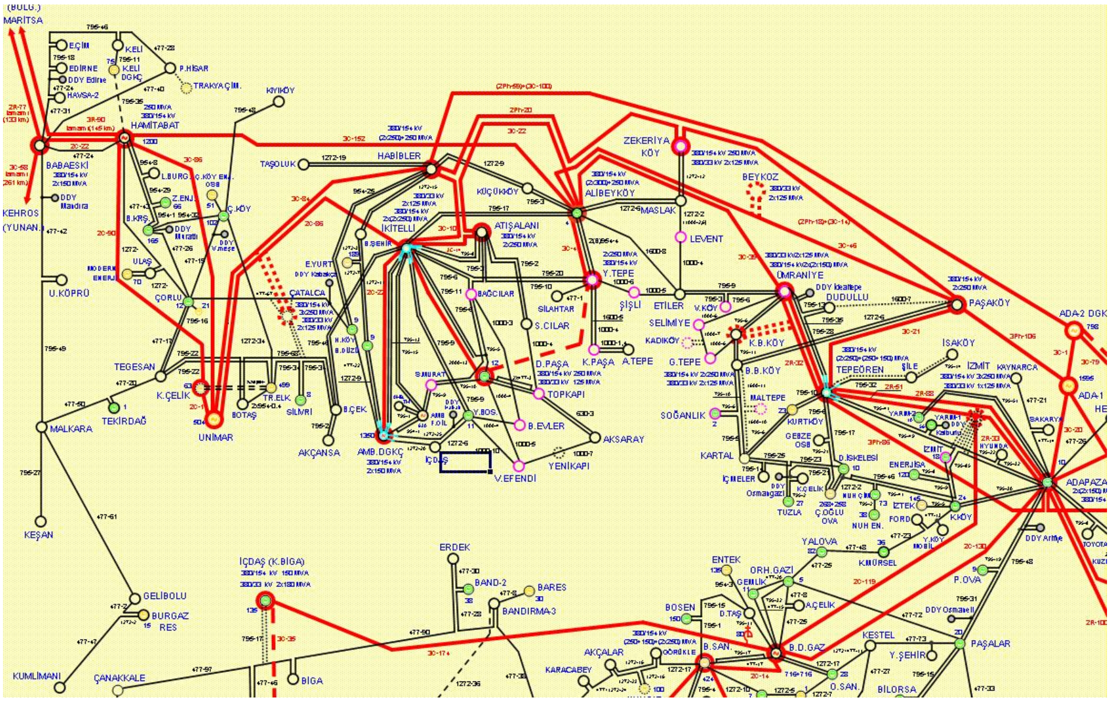

Figure 3.3: One-line diagram of the 225-bus system of Istanbul Region
Source: TEİAŞ

The power-flow solution is the major part of our study. We run the power-flow program using Newton-Raphson method to obtain the power-flow solution. Our program considers the reactive power limits of generator buses in the systems. As you may know, such constraints make power-flow difficult to convergence. However, the program reaches a solution successfully for each power system we used. The power-flow solution of the system is taken as a base case. After this point, we develop P-V and Q-V curves based on the methodology we describe below.

The methodology that we follow for development of a full P-V curve is as follows:

1. Choose a load bus at which the real power P is incrementally changed. The power generated from the newly-added generator bus will be transferred to this bus. This could be a load that is transferred power from the. We call the chosen bus the candidate bus.

2. Increase the real power P by 0.75 p.u. at the candidate bus. The real power output of the newly-added generator should simultaneously provide this increase. Note that except this change, nothing else changes in the data. Run the power-flow program with these changes. Obtain a new voltage value at the candidate bus against the increased P value.

3. Iterate the processes at step 2 until the power-flow does no more converge.

4. Run the program that plots the P-V curve using the calculated voltages corresponding to incrementally changed P values at the candidate bus.

5. Compute the maximum permissible real power P_{max}.

Using the methodology for generating P-V curves which we discuss above, we generate P-V curves for load buses 5, 8, and 9 of the 20-bus IEEE system. They are given in Figures 3.4, 3.5, and 3.6. The real power limit of the given buses are easily obtained from the P-V curves in these figures.

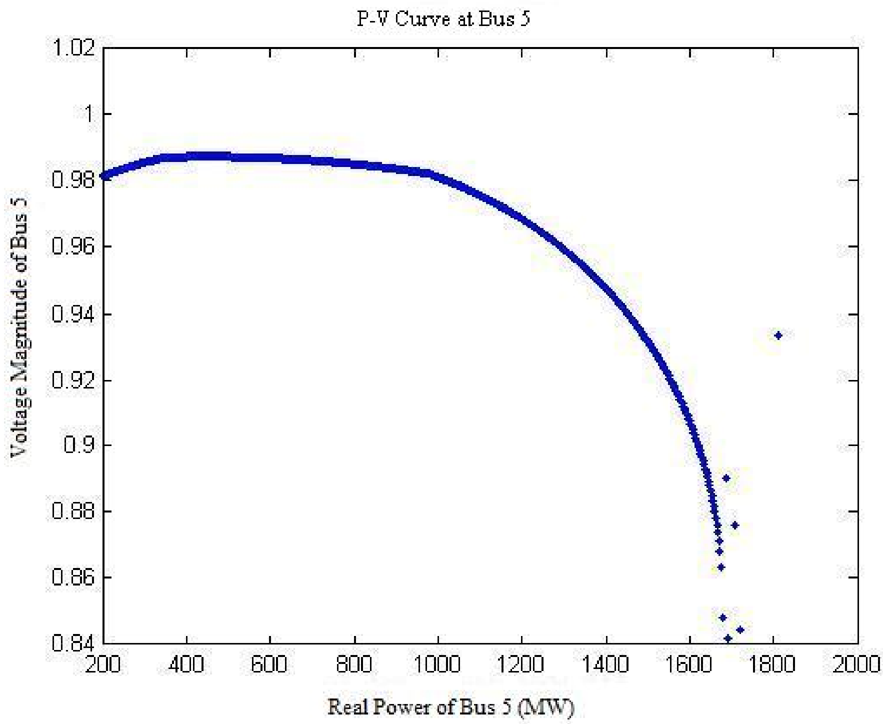

Figure 3.4 : P-V Curve (Bus 5 at the system IEEE20)

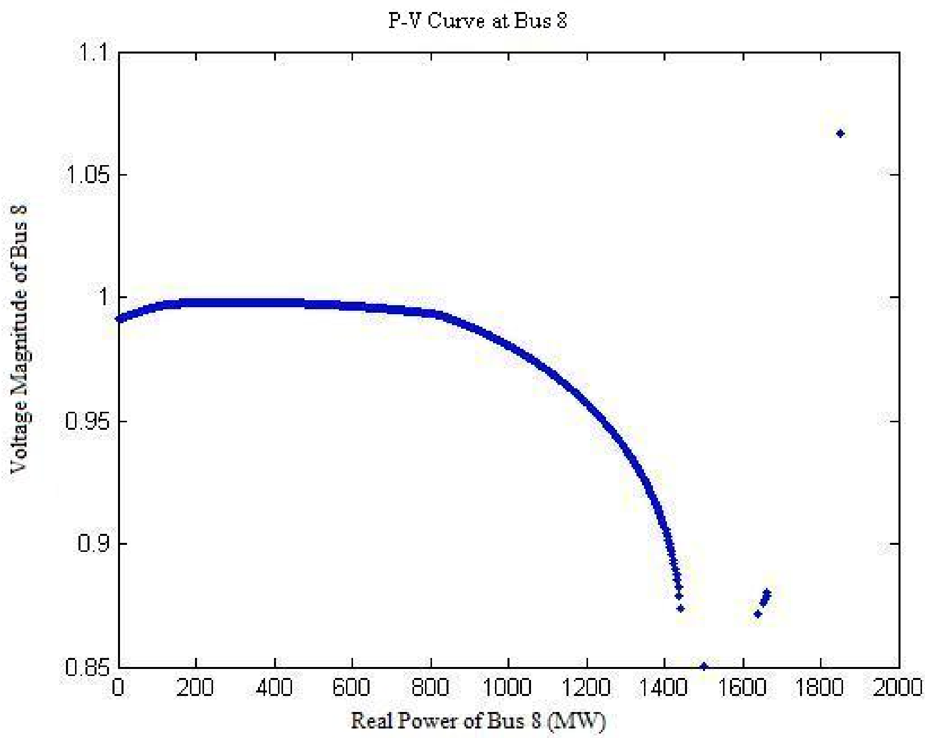

Figure 3.5: P-V Curve (Bus 8 at the system IEEE20)

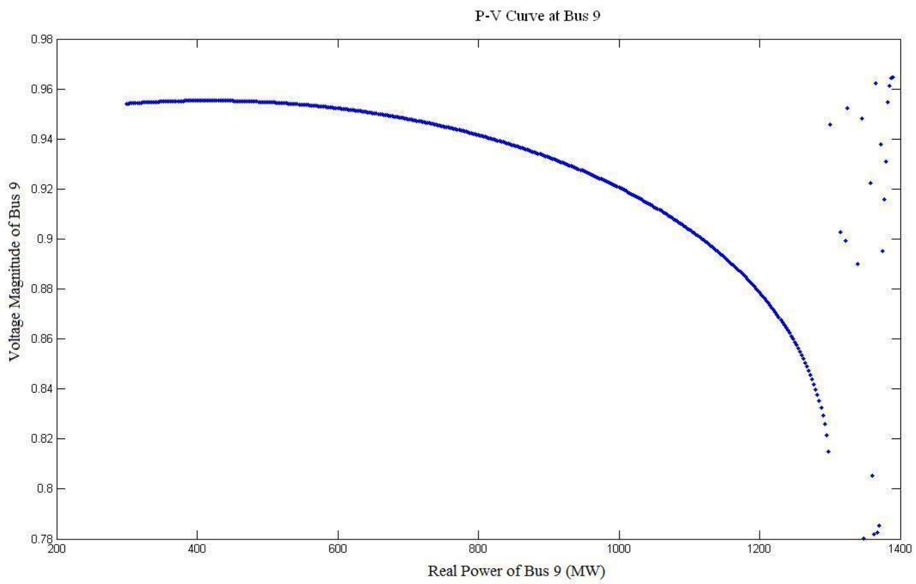

Figure 3.6: P-V Curve (Bus 19 at the system IEEE20)

The P-V curves for load buses 9, 19, and 79 of the 225-bus system of Istanbul Region are given in Figures 3.7, 3.8, and 3.9.

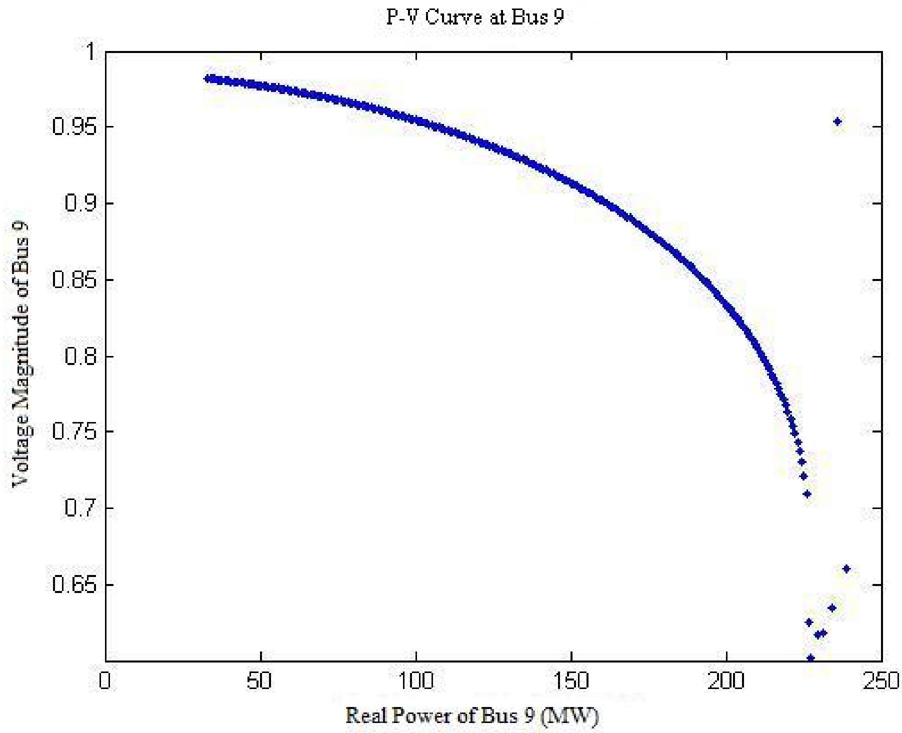

Figure 3.7: P-V Curve (Bus 9 at the system of Istanbul225)

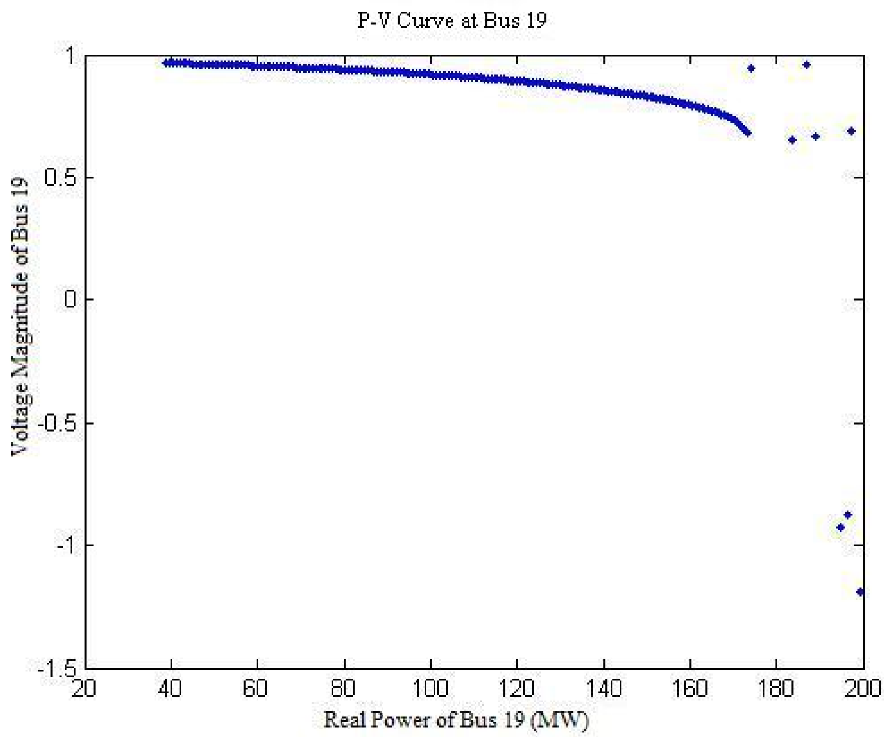

Figure 3.8: P-V Curve (Bus 19 at the system Istanbul225)

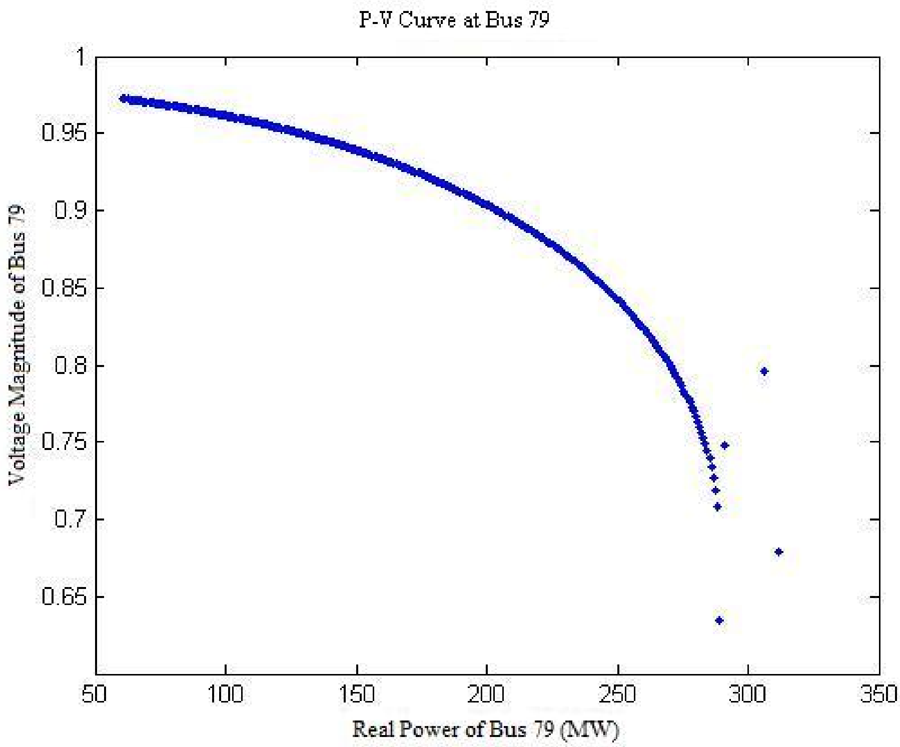

Figure 3.9: P-V Curve (Bus 79 at the system Istanbul225)

A general belief in power system management is that after a power-flow solution misses the convergency, the system solution does not converge again. However, the behavior of the points after the nose of the curve in the figures above is contrary to that general belief; interestingly enough, such convergence can occur after divergence.

The methodology that we follow for development of a full Q-V curve is as follows:

1. Choose a load bus at which the reactive power Q is incrementally increased. We call the chosen bus the candidate bus as in the methodology for P-V curves.

2. The reactive power output of each generator should be allowed to adjust as the Q-V analysis progresses. Increase the real power Q by 0.75 p.u. at the candidate bus. Note that except this change, nothing else changes in the data. Run the power-flow program with these changes. Obtain a new voltage value at the candidate bus against the increased Q value.

3. Iterate the processes at step 2 until the power-flow does no more converge.

4. To reach the nose of the curve closely, take the last case at which the power-flow converges as the base case

5. Run the program that plots the Q-V curve using the calculated voltages corresponding to incrementally changed Q values at the candidate bus.

6. Compute the maximum reactive power Q_{max} of the candidate bus.

Using the methodology for generating Q-V curves which we discuss above, we generate Q-V curves for load buses 5, 8, and 9 of the 20-bus IEEE system. They are given in Figures 3.10, 3.11, and 3.12. The reactive power limit of the given buses are easily obtained from the Q-V curves in these figures. Similar points after the nose of curve are also observed at the Q-V curves of the same buses.

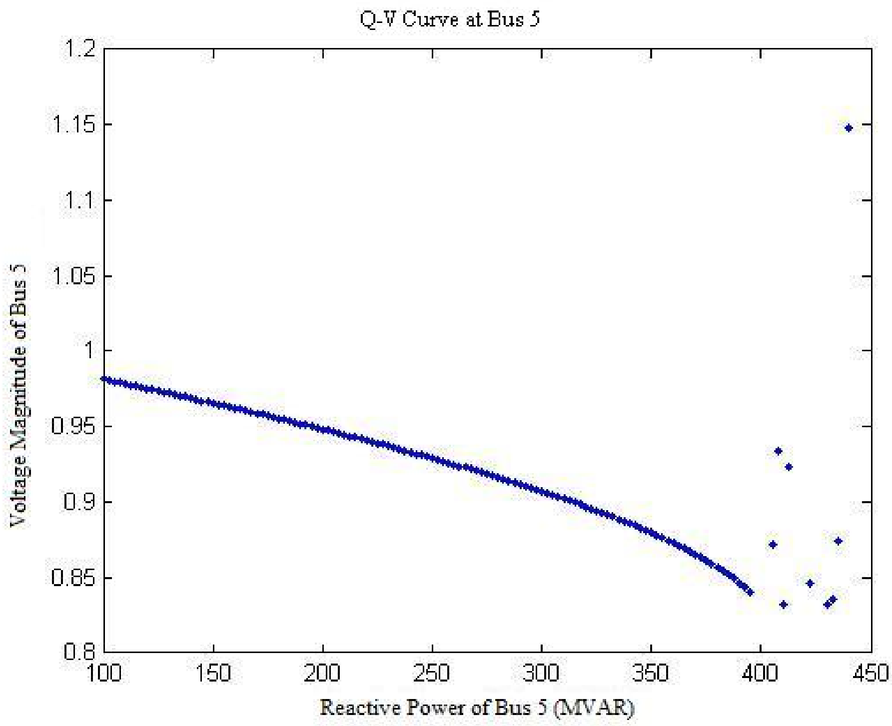

Figure 3.10: Q-V Curve (Bus 5 at the system IEEE20)

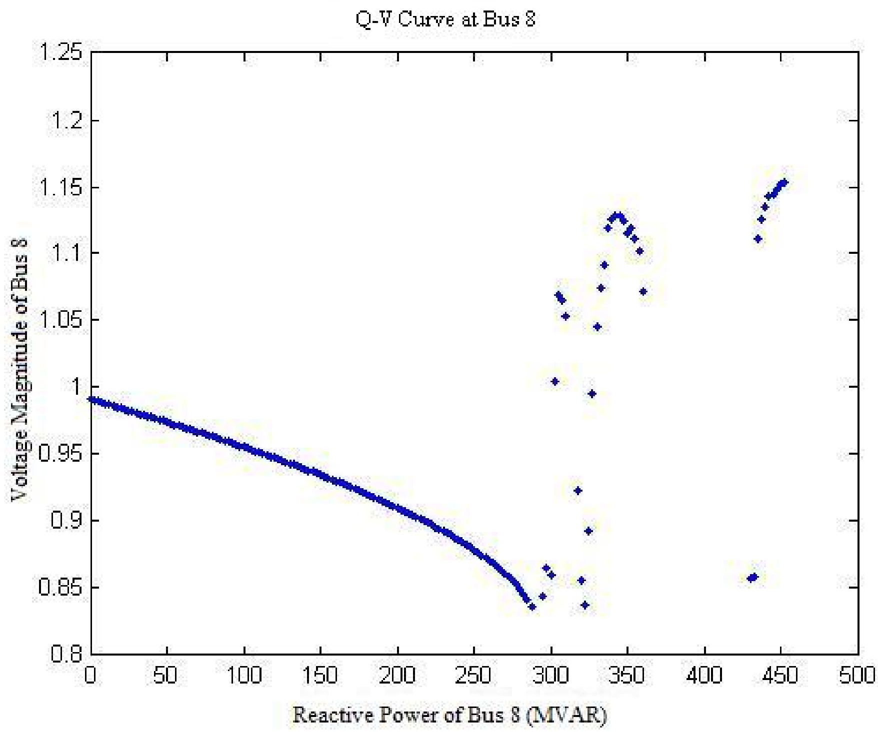

Figure 3.11: Q-V Curve (Bus 8 at the system IEEE20)

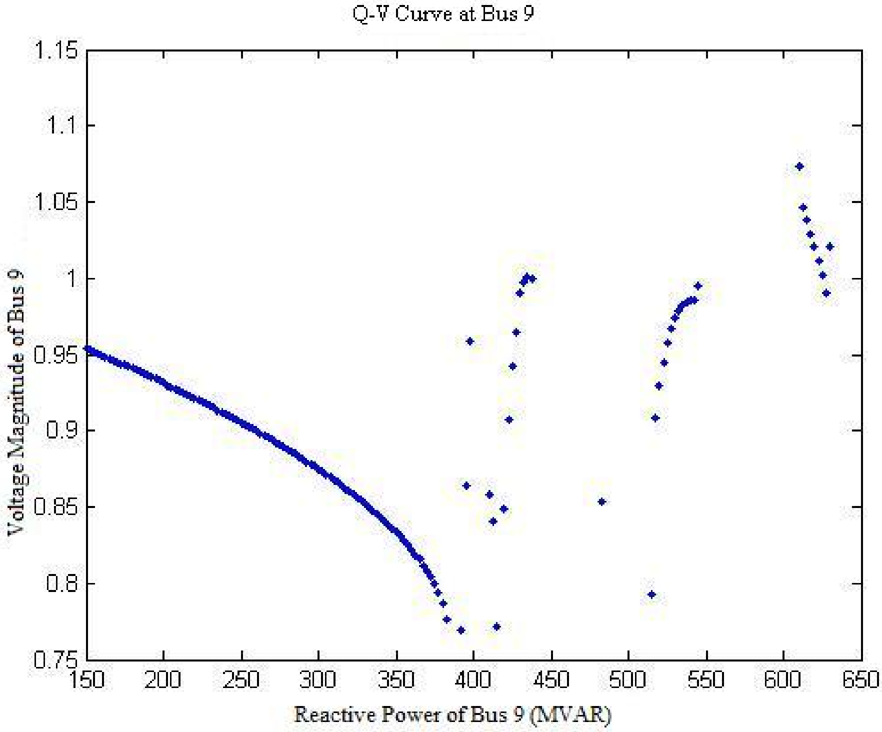

Figure 3.12: Q-V Curve (Bus 9 at the system IEEE20)

The Q-V curves for load buses 9,19, and 79 of the 225-bus system of Istanbul Region are given in Figures 3.13, 3.14, and 3.15.

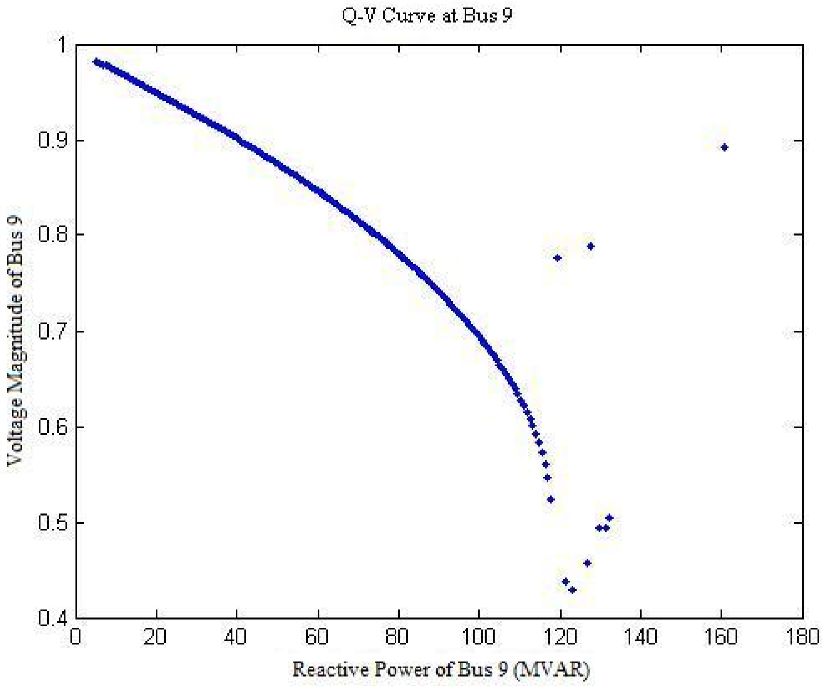

Figure 3.13: Q-V Curve (Bus 9 at the system Istanbul225)

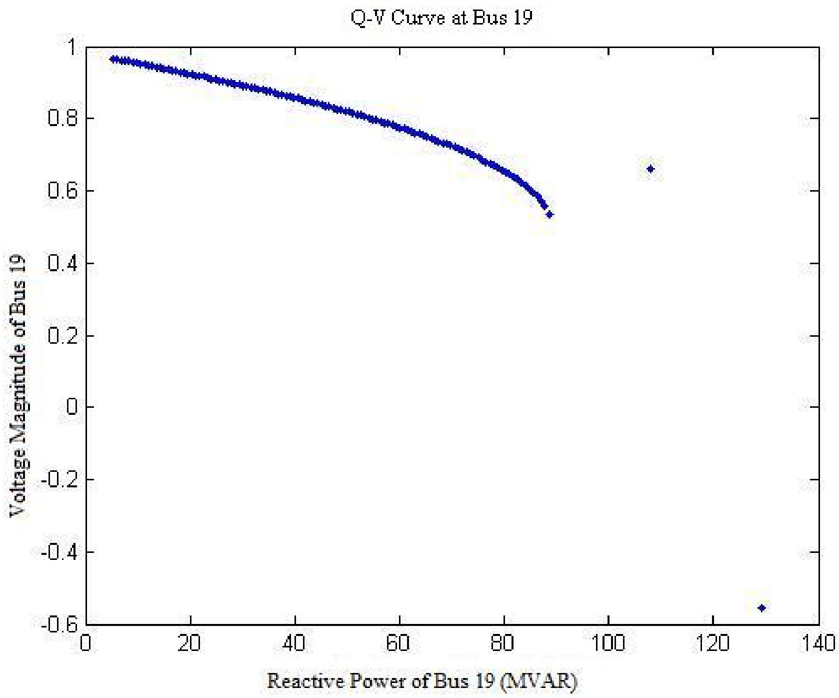

Figure 3.14: Q-V Curve (Bus 19 at the system Istanbul225)

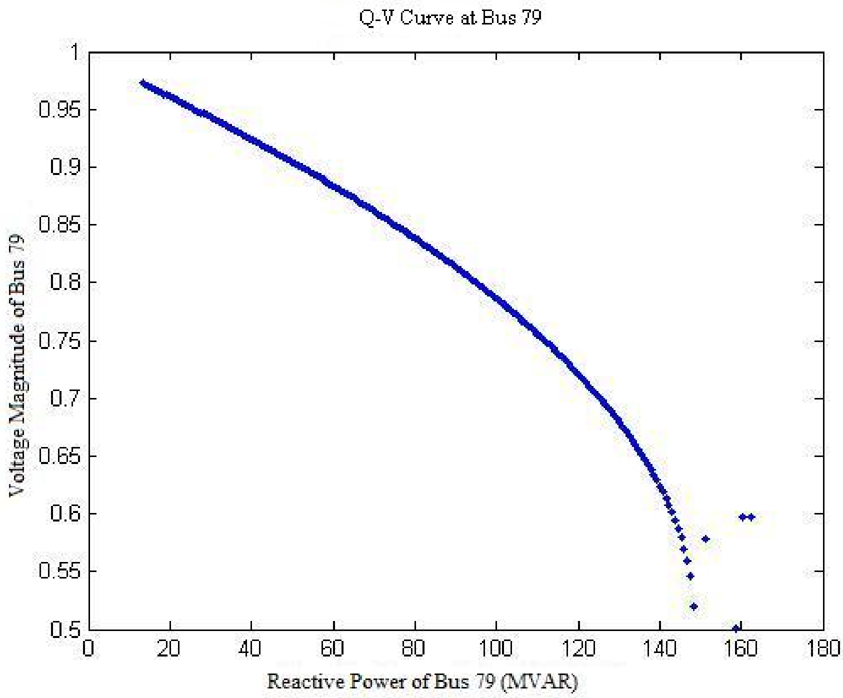

Figure 3.15: Q-V Curve (Bus 79 at the system Istanbul225)

4. CONCLUSION

In the first chapter, we give definition of transmission congestion; discuss causes and importance of analysis of transmission congestion. The literature about transmission congestion is rewieved. Subsequently, objectives and methodologies of this study are also mentioned.

In the second chapter, power-flow analysis is described mathematically in details. Power-flow equations and power-flow solution using Newton-Raphson method are also studied. We give the explanation of power-flow program and flowchart of this program at the end of this chapter.

In the third chapter, we describe P-V and Q-V curves and explain how to compute real and reactive power capacities using P-V and Q-V curves. We also discuss research methodology that we follow for assessment of real and reactive power capacities of candidate bus and show our results with P-V and Q-V curves for various load buses of the 20-bus IEEE system and the 225-bus system of Istanbul Region. We obtain interesting points after the nose in the P-V and Q-V curves of some buses. These points after nose are observed in P-V and Q-V curves of almost all buses of these two power system. A general belief in power system management is that after a power-flow solution misses the convergency, the system solution does not converge again. These points show that convergence can occur after divergence. Due to these outputs, these curves must be analyzed mathematically details to understand the behavior of these points.

In conclusion, we observe the congestion effects of newly-added generator to the power system by our thesis study. For example, a utility company would like to sell power to some load centers or cities. However, it is not that simple to transfer power between utility company regarding consumption centers if the transmission lines become congested under new loading conditions. In such a case, our study provides the utility company with the information that whether or not the transmission system turns out to be congested.

4.1 CONTRIBUTIONS

We have developed a comprehensive power-flow program that also includes the reactive power limits of the generators using MATLAB. Two different power systems, one of which is a small scale system and other is a middle scale system, are analyzed closely for transmission congestion. The P-V and Q-V curves that are corresponding to candidate buses are obtained. This work provides information for utilities to manage the power grid effectively and power investors to invest in correct resources at correct places.

4.2 FURTHER STUDY

The power-flow program can be elaborated; as you may know, the program we develop does apply two different power systems. However, it becomes much more professional by running the program for various different power systems. P-V and Q-V curves can be analyzed mathematically in details, since the points after the nose of curve can change the general belief about the convergence of the power-flow solutions.

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APPENDICES

APPENDIX A. PROGRAMS

A.1 POWER-FLOW PROGRAM

```
function [bus,gen,branch,P,Q]=pwr_flw(ieeefilename,addnum,Qlim)
if nargin<=0
    fprintf('You must give at least one input.\nPlease recall this function
with input.\n');
else
    [baseMVA,bus,gen,branch] = feval(ieeefilename);
    if nargin>=2
    [bus,gen,branch]=addfun(bus,gen,branch,addnum);
    end
    [bus,gen,branch,ext]=intnum(bus,gen,branch);
    [fbus, tbus,  fbuslen, Y, a, b, y]=ybus(branch,bus,baseMVA);
    data_formating;
    if nargin==3
        pfnewton_Qlim;
    else
        pfnewton;
    end
    [bus,gen,branch]=extnum(bus,gen,branch,ext);
    printout;
end
```

A.2 PROGRAM FOR MODIFYING THE POWER SYSTEM DATA

```
function [bus,gen,branch]=addfun(bus,gen,branch,addnum)
for d=1:addnum
    q=input('If you change bus data,\npress 1 to update a bus data, \npress 2
to enter new bus data, \nif not press zero\n');
    if q==2
        fprintf(' Bus   Type     Pd       Qd       Gs       Bs   area    Vm
Va     baseKV   zone   Vmax\n');

fprintf('==================================================================
=======================\n');
        newbus=input('\nEnter bus data of new bus\n');
        if newbus(2)==2
            fprintf(' Bus     Pg     Qg     Qmax     Qmin    Vsp   baseMVA
status    Pmax      Pmin\n');
fprintf('==================================================================
==============\n');
            newgen=input('Enter generator data of new bus\n');
        end
        fprintf('Fbus   Tbus     R       B      Ratea     Rateb     Ratec
Ratio   Angle  status\n');
fprintf('==================================================================
=============\n');
        newbranch=input('Enter branch data of new bus\n');
        bus=[bus;newbus];
        gen=[gen;newgen];
        branch=[branch;newbranch];
    end
    if q==1
        x=input('Enter bus number\n');
        i=1;
        while x~=bus(i,1)
            i=i+1;
        end
        fprintf(' Bus   Type     Pd       Qd       Gs       Bs   area    Vm
Va     baseKV   zone   Vmax\n');
fprintf('==================================================================
=======================\n');
fprintf('%4d%5d%10.3f%9.3f%9.3f%9.3f%5d%9.3f%9.3f%10.3f%5d%9.3f\n',bus(i,[1:12
]));
        upbus=input('Enter new data of selected bus\n');
        bus(i,1:12)=upbus;
        if upbus(2)~=1
            k=input('Is generation data new or update? Press 1 for new, 2 for
update\n');
            if k==1
                i=1;
                fprintf(' Bus     Pg     Qg     Qmax     Qmin    Vsp   baseMVA
status    Pmax      Pmin\n');
fprintf('==================================================================
==============\n');
                upgen=input('Enter new generation data of selected bus\n');
                while x>gen(i,1)
                    i=i+1;
                    if i>length(gen)
                        break
                    end
                end
                if i<=length(gen)
                    gen=[gen(1:i-1,:);upgen;gen(i:end,:)];
                else
                    gen=[gen;upgen];
                end
```

```
            else
                i=1;
                while x~=gen(i,1)
                    i=i+1;
                end
                fprintf(' Bus     Pg     Qg     Qmax       Qmin      Vsp
baseMVA  status     Pmax       Pmin\n');
fprintf('====================================================================
===================\n');
 fprintf('%4d%8d%7.3f%10.3f%9.3f%10.3f%8d%11.3f%11.3f%10.3f\n',gen(i,1:10));
                upgen=input('Enter new generation data of selected bus,\n');
                gen(i,:)=upgen;
            end
        end
    end
end
```

A.3 PROGRAM FOR BUS ADMITTANCE MATRIX

```
function [fbus, tbus,  fbuslen, Y, a, b, y]=ybus(branch,bus,baseMVA)
fbus=branch(:,1);
tbus=branch(:,2);
R=branch(:,3);
X=branch(:,4);
b=branch(:,5)/2;
Gs=bus(:,5)/baseMVA;
Bs=bus(:,6)/baseMVA;
fbuslen=length(branch(:,1));
maxbus=max(max(fbus),max(tbus));
Z=R+j*X;
y=ones(fbuslen,1)./Z;
Y=zeros(maxbus,maxbus);
a=branch(:,9);
for  n=1:maxbus
    Y(n,n)=Gs(n)+j*Bs(n);
    for k=1:fbuslen
        if a(k)==0
            a(k)=1;
        end
        if fbus(k)==n
            Y(n,n) = Y(n,n)+y(k)/(a(k)^2) + j*b(k);
        elseif tbus(k)==n
            Y(n,n) = Y(n,n)+y(k) + j*b(k);
        end
    end
end
for i=1:fbuslen
    Y(fbus(i),tbus(i))=Y(fbus(i),tbus(i))-y(i)/a(i);
    Y(tbus(i),fbus(i))=Y(fbus(i),tbus(i));
end
```

A.4 PROGRAM FOR NEWTON-RAPHSON METHOD

A.4.1 Main Program for Newton-Raphson Method

```
m=2*buslen-npv-2*ns;
accu=0.001;
maxiter=100;
angconv=0;
error=1;
iter=1;
while error>=accu & iter<=maxiter
    JM=zeros(m,m);
    for n=1:buslen
        j1r=n-s_index(n);
        j3r=buslen+n-pv_index(n)-s_index(n)-ns;
        J11=0; J22=0; J33=0; J44=0;
        for i=1:buslen
            if i==n
                continue
            else
                J11=J11+Vm(n)*Vm(i)*Ym(n,i)*sin(Yang(n,i)-angle(n)+angle(i));
                J33=J33+Vm(n)*Vm(i)*Ym(n,i)*cos(Yang(n,i)-angle(n)+angle(i));
                if bustype(n)~=3
                    J22=J22+Vm(i)*Ym(n,i)*cos(Yang(n,i)- angle(n)+angle(i));
                    J44=J44+Vm(i)*Ym(n,i)*sin(Yang(n,i)- angle(n)+angle(i));
                end
                if bustype(n)~=3 & bustype(i)~=3
                    j2c=buslen+i-pv_index(i)-s_index(i)-ns;
                    j1c=i-s_index(i);
                    JM(j1r,j1c) =-Vm(n)*Vm(i)*Ym(n,i)*sin(Yang(n,i)-
angle(n)+angle(i));
                    if bustype(i)==1
                        JM(j1r,j2c)=Vm(n)*Ym(n,i)*cos(Yang(n,i)-
angle(n)+angle(i));
                    end
                    if bustype(n)==1
                        JM(j3r,j1c)=-Vm(n)*Vm(i)*Ym(n,i)*cos(Yang(n,i)-
angle(n)+angle(i));
                    end
                    if bustype(n)==1 & bustype(i)==1
                        JM(j3r,j2c)=-Vm(n)*Ym(n,i)*sin(Yang(n,i)-
angle(n)+angle(i));
                    end
                end
            end
        end
        Pk=Vm(n)^2*Ym(n,n)*cos(Yang(n,n))+J33;
        Qk=-Vm(n)^2*Ym(n,n)*sin(Yang(n,n))-J11;
        if bustype(n)~=3
            JM(j1r,j1r)=J11;
            dPQ(j1r)=P(n)-Pk;
        end
        if bustype(n)==1
            JM(j1r,j3r)=2*Vm(n)*Ym(n,n)*cos(Yang(n,n))+J22;
            JM(j3r,j1r)=J33;
            JM(j3r,j3r)=-2*Vm(n)*Ym(n,n)*sin(Yang(n,n))-J44;
                  dPQ(j3r)=Q(n)-Qk;
        end
    end
    dsV=JM\dPQ';
    for n=1:buslen
        j1r=n-s_index(n);
        j3r=buslen+n-pv_index(n)-s_index(n)-ns;
```

```
        if bustype(n)~=3
            angle(n)=angle(n)+dsV(j1r);
        end
        if bustype(n)==1
            Vm(n)=Vm(n)+dsV(j3r);
        end
    end
    error=max(abs(dPQ));
    iter=iter+1;
    V=Vm.*cos(angle)+j*Vm.*sin(angle);
    S_gen=V(gennum).*conj(Y(gennum,:)*V);
    Qg(gennum)=imag(S_gen)*baseMVA+Qd(gennum);
    sb_find=find(gennum==sb);
    Pg(sb)=real(S_gen(sb_find))*baseMVA+Pd(sb
    flag=0;
    for i=1:genlen
        if Qg(gennum(i))<Qmin(gennum(i))
            Q(gennum(i))=(Qmin(gennum(i))-Qd(gennum(i)))/baseMVA;
            flag=flag+1;
            tmp(flag)=gennum(i);
        elseif Qg(gennum(i))>Qmax(gennum(i))
            Q(gennum(i))=(Qmax(gennum(i))-Qd(gennum(i)))/baseMVA;
            flag=flag+1;
            tmp(flag)=gennum(i);
        end
    end
    if flag ~=0

[Vm,angle,error]=Qlimit(tmp,gen,bustype,buslen,s_index,ns,Vm,Ym,Yang,angle,P,Q
);
        if error<accu
            bustype(tmp)=1;
        end
        clear tmp;
    end
end
clear S_fr S_to S_loss
angconv=180/pi*angle;
S_fr=baseMVA*V(fbus).*conj((V(fbus)-
V(tbus).*a).*y+V(fbus).*(j*b))./(a.*conj(a));
S_to=baseMVA*V(tbus).*conj((V(tbus)-V(fbus)./a).*y+V(tbus).*(j*b));
S_loss=S_fr+S_to;
bus(:,8)=Vm'; bus(:,9)=angconv';
```

A.4.2 Program for Reactive Power Limit

```
function
[Vm,angle,error]=Qlimit(tmp,gen,bustype,buslen,s_index,ns,Vm,Ym,Yang,angle,P,Q
)
bustype(tmp)=1;
pv=find(bustype==2);
npv=length(pv);
pv_index=zeros(1,buslen);
for i=1:npv %define PV index
    if i==npv
        if pv(i)==buslen
            pv_index(1,buslen)=i;
        end
        pv_index(1,pv(i):buslen)=i;
    else
        pv_index(1,pv(i):(pv(i+1)-1))=i;
    end
end
m=2*buslen-npv-2*ns;
JM=zeros(m,m);
```

```
for n=1:buslen
    j1r=n-s_index(n);
    j3r=buslen+n-pv_index(n)-s_index(n)-ns;
    J11=0; J22=0; J33=0; J44=0;
    for i=1:buslen
        if i==n
            continue
        else
            J11=J11+Vm(n)*Vm(i)*Ym(n,i)*sin(Yang(n,i)-angle(n)+angle(i));
            J33=J33+Vm(n)*Vm(i)*Ym(n,i)*cos(Yang(n,i)-angle(n)+angle(i));
            if bustype(n)~=3
                J22=J22+Vm(i)*Ym(n,i)*cos(Yang(n,i)- angle(n)+angle(i));
                J44=J44+Vm(i)*Ym(n,i)*sin(Yang(n,i)- angle(n)+angle(i));
            end
            if bustype(n)~=3 & bustype(i)~=3
                j2c=buslen+i-pv_index(i)-s_index(i)-ns;
                j1c=i-s_index(i);
                JM(j1r,j1c) =-Vm(n)*Vm(i)*Ym(n,i)*sin(Yang(n,i)-
angle(n)+angle(i));
                if bustype(i)==1
                    JM(j1r,j2c)=Vm(n)*Ym(n,i)*cos(Yang(n,i)-
angle(n)+angle(i));
                end
                if bustype(n)==1
                    JM(j3r,j1c)=-Vm(n)*Vm(i)*Ym(n,i)*cos(Yang(n,i)-
angle(n)+angle(i));
                end
                if bustype(n)==1 & bustype(i)==1
                    JM(j3r,j2c)=-Vm(n)*Ym(n,i)*sin(Yang(n,i)-
angle(n)+angle(i));
                end
            end
        end
    end
    Pk=Vm(n)^2*Ym(n,n)*cos(Yang(n,n))+J33;
    Qk=-Vm(n)^2*Ym(n,n)*sin(Yang(n,n))-J11;
    if bustype(n)~=3
        JM(j1r,j1r)=J11;
        dPQ(j1r)=P(n)-Pk;
    end
    if bustype(n)==1
        JM(j1r,j3r)=2*Vm(n)*Ym(n,n)*cos(Yang(n,n))+J22;
        JM(j3r,j1r)=J33;
        JM(j3r,j3r)=-2*Vm(n)*Ym(n,n)*sin(Yang(n,n))-J44;
        dPQ(j3r)=Q(n)-Qk;
    end
end
dsV=JM\dPQ';
for n=1:buslen
    j1r=n-s_index(n);
    j3r=buslen+n-pv_index(n)-s_index(n)-ns;
    if bustype(n)~=3
        angle(n)=angle(n)+dsV(j1r);
    end
    if bustype(n)==1
        Vm(n)=Vm(n)+dsV(j3r);
    end
end
error=max(abs(dPQ));
```

A.5 FUNCTION FOR NUMERICAL RESULT OF POWER-FLOW SOLUTION

```
filename = strcat(ieeefilename,'_printout.txt');
fid=fopen(filename,'w+');
head1='POWER-FLOW SOLUTION by NEWTON-RAPHSON METHOD';
busnum=bus(:,1);
fprintf(fid,'%64s \n\n\n\n',head1);
fprintf(fid,'Maximum Power mismatch = %.10f. \n',error);
fprintf(fid,'Power flow converged in %3d iterations. \n\n\n\n',iter-1);
fprintf(fid,
'\n===========================================================================
=====');
fprintf(fid, '\n|     System Summary
|');
fprintf(fid,
'\n===========================================================================
=====');
fprintf(fid, '\n\nHow many?                How much?              P (MW)
Q (MVAr)');
fprintf(fid, '\n--------------------    ------------------  ------------  -
----------------');
fprintf(fid, '\nBuses         %6d     Total Gen Capacity   %7.1f
%7.1f ', buslen,sum(Pg),sum(Qg));
fprintf(fid, '\nGenerators     %5d     On-line Capacity     %7.1f
%7.1f', npv,sum(Pg),sum(Qg));
fprintf(fid, '\nLoads          %5d     Load                 %7.1f
%7.1f', npq,sum(Pd),sum(Qd));
fprintf(fid, '\nShunts         %5d     Shunt (inj)          %7.1f
%7.1f', nqsh,sum(Psh),sum(Qsh));
fprintf(fid, '\nBranches       %5d     Losses               %7.2f
%7.2f', length(branch),sum(real(S_loss)),sum(imag(S_loss)) );
fprintf(fid,
'\n===========================================================================
=====');
fprintf(fid, '\n|     Bus Data
|');
fprintf(fid,
'\n===========================================================================
=====');
fprintf(fid, '\n Bus      Voltage          Generation             Load
');
fprintf(fid, '\n  #   Mag(pu) Ang(deg)   P (MW)   Q (MVAr)   P (MW)   Q
(MVAr)');
fprintf(fid, '\n----- ------- --------  --------  --------  --------  --------
');
for n=1:buslen
    fprintf(fid, '\n%5d%7.3f%9.3f',bus(n, [1,8,9]));%busnumber,Vm,angle
    fprintf(fid, '%10.2f%10.2f ',Pg(n),Qg(n));%Pg,Qg
    fprintf(fid, '%10.2f%9.2f',Pd(n),Qd(n));%Pd,Qd
end
fprintf(fid, '\n                        --------  --------  --------  --------
');
fprintf(fid, '\n               Total: %9.2f %9.2f %9.2f
%9.2f',sum(Pg),sum(Qg),sum(Pd),sum(Qd));
fprintf(fid, '\n');
fprintf(fid,
'\n===========================================================================
=====');
fprintf(fid, '\n|     Branch Data
|');
fprintf(fid,
\n===========================================================================
====');
```

```
fprintf(fid, '\nBrnch   From   To    From Bus Injection   To Bus Injection
Loss   ');
fprintf(fid, '\n  #     Bus    Bus    P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
P (MW)   Q (MVAr)');
fprintf(fid, '\n-----  -----  -----  --------  --------  --------  --------  -
-------  --------');
for n=1:fbuslen
    fprintf(fid, '\n%4d%7d%7d%10.2f%10.2f%10.2f%10.2f%10.2f%10.2f',...

n,branch(n,[1,2]),real(S_fr(n)),imag(S_fr(n)),real(S_to(n)),imag(S_to(n)),real
(S_loss(n)),imag(S_loss(n)));
end
fprintf(fid, '\n                                                              -
-------  --------');
fprintf(fid, '\n
Total:%10.2f%10.2f',sum(real(S_loss)),sum(imag(S_loss)));
fprintf(fid, '\n');

fclose(fid);
```

A.6 PROGRAM FOR PLOTTING P-V AND Q-V CURVE

A.6.1 Program for Plotting P-V Curve

```
del=0;
num=9;
for inx=1:1000
    [baseMVA,bus,gen,branch,buscoord,busname]=gr_data;
    newbus=[21  2      0.00     0.00    0.000 0.000   1   1.02000    0.000
230.00  0    1.06000  0.94000];
    newgen=[21   0     0.00   500.00     0.00  0.98000   100.00    1
1000.00     0.00 ];
    newbranch=[21   19   0.00300  0.02500  0.06000   100.00   100.00    100.00
1.00000    0.000     1];
    bus=[bus;newbus];
    gen=[gen;newgen];
    branch=[branch;newbranch];
    bus(num,3)=bus(num,3)+0.75*(inx);
    gen(7,2)=gen(7,2)+0.75*(inx);
    [fbus, tbus,  fbuslen, Y, a, b, y]=ybus(branch,bus,baseMVA);
    data_formating;
    pfnewton_Qlim;
    if error>accu
        del=del+1;
    else
        P_stk(inx-del)=bus(num,3);
        V_stk(inx-del)=Vm(num);
    end
    if del==50
        break
    end
end
plot(P_stk,V_stk,'.')
xlabel('Real Power of Bus 9 (MW)');
ylabel('Voltage Magnitude of Bus 9');
```

A.6.2 Program for Plotting Q-V Curve

```
del=0;
num=9;
for inx=1:1000
    [baseMVA,bus,gen,branch,buscoord,busname]=gr_data;
    bus(num,4)=bus(num,4)+0.75*(inx-1);
    [fbus, tbus,  fbuslen, Y, a, b, y]=ybus(branch,bus,baseMVA);
    data_formating;
    pfnewton_Qlim;
    if error>accu
        del=del+1;
    else
        Q_stk(inx-del)=bus(num,4);
        V_stk(inx-del)=Vm(num);
    end
    if del==50
        break
    end
end
plot(Q_stk,V_stk,'.')
xlabel('Reactive Power of Bus 9 (MVAR)');
ylabel('Voltage Magnitude of Bus 9');
```

CURRICULUM VITAE

Name and Surname	: Sıtkı GÜNER
Permanent Address	:Barış Mh. Zafer Cd. Birlik Ap. No: 3 D:28 Beylikdüzü/İstanbul
Birth Place and Year	: Antalya 1983
Languages	: Turkish (native) - English
High School	: Aksu Anadolu Öğretmen Lisesi 1997 - 2001
Undergraduate Degree	:Bahçeşehir Üniversitesi 2001 - 2006
Graduate Degree	: Bahçeşehir Üniversitesi 2006 - 2009
Name of Institute	: Institute of Science
Name of Program	: Electrical & Electronics Engineering
Work Experience	: BAHÇEŞEHİR UNIVERSITY 2006 - Ongoing Engineering Department