www.dergipark.gov.tr
ISSN:2148-3736
El-Cezerî Fen ve Mühendislik Dergisi
Cilt: 7, No: 1, 2020 (179-188)

El-Cezerî Journal of Science and Engineering
Vol: 7, No: 1, 2020 (179-188)
DOI: 10.31202/ecjse.602441

ECJSE

Research Paper / Makale

Investigation of Voltage Stability in Different Operating Conditions

Salih TOSUN*, Ali ÖZTÜRK

Duzce University, Technology Faculty, Department of Electrical and Electronics Engineering, 81620, Duzce/Turkey
salihtosun@duzce.edu.tr

Received/Geliş: 06.08.2019 **Accepted/Kabul:** 10.10.2019

Abstract: In our developing world, the need for electric energy is increasing. In order to meet this demand, new power transmission systems as well as new sources are needed. However, the cost factor in creating power systems has led to the efficient, stable and reliable operation of the existing system. Therefore, how the existing power systems behave in extraordinary situations needs to be examined and known. In this study, the IEEE 6-bus power system is considered. Stability analysis of the system was made by creating various situations in this power system. This simulation work was carried out with the Power Systems Analysis Program (PSAT).

Keywords: Voltage Stability; Power System; Load Flow

Gerilim Kararlılığının Farklı İşletme Şartlarında İncelenmesi

Öz: Gelişen dünyamızda elektrik enerjisine olan ihtiyaç giderek artmaktadır. Bu talebin karşılanabilmesi için yeni kaynakların yanı sıra yeni güç iletim sistemlerine de gereksinim vardır. Ancak güç sistemlerinin oluşturulmasındaki maliyet unsuru mevcut sistemin en verimli, kararlı ve güvenilir şekilde işletilmesini ortaya çıkarmıştır. Bundan dolayı mevcut güç sistemlerinin olağanüstü durumlarda nasıl davranacağının da incelenmesi ve bilinmesi gereklidir. Yapılan bu çalışmada IEEE'nin 6 baralı güç sistemi ele alınmıştır. Bu güç sisteminde çeşitli durumlar oluşturularak sisteminin kararlılık analizleri yapılmıştır. Bu benzetim çalışması, Güç Sistemleri Analizi Programı (PSAT) ile gerçekleştirilmiştir.

Anahtar kelimeler: Gerilim Kararlılığı; Güç Sistemi; Yük Akışı

1. Introduction

One of the most important problems experienced in electric power systems is to provide reliable and continuous energy to consumers. Depending on the development of the technology, the need for electrical energy is increasing at everyday rates. The fact that production and consumption centers are far from each other has brought energy to move along long transmission lines. As a result, it has brought some obligations and problems in power systems. Problems caused by the loss of the losses and transmission of faults along transmission lines are also among the subjects of the researchers. One of the important problems that long-distance energy carrier has is voltage stability [1]. The instability caused by the distances to the consumption points of energy production centers is expressed as voltage instability. This voltage instability is directly related to the maximum power carrying capacities of energy transmission lines [2]. The graphs in which this voltage stability is most easily observed are P-V curves obtained from the load bus. The power drawn from the load bus increases the losses on the line and the voltage drop on the line. This voltage drop across the load bus must not fall below a certain value for the consumer. This value is expressed as the critical bus voltage value. Active power consumed at this time is expressed as critical power value. As the value of the voltage decreases, the operation of the system becomes more difficult. In this case, it is

How to cite this article
Tosun, S., Öztürk, A., "*Investigation of Voltage Stability in Different Operating Conditions*" El-Cezerî Journal of Science and Engineering, 2020, 7 (1); 179-188.

Bu makaleye atıf yapmak için
Tosun, S., Öztürk, A., *"Gerilim Kararlılığının Farklı İşletme Şartlarında İncelenmesi"* El-Cezerî Fen ve Mühendislik Dergisi 2020, 7 (1); 179-188.

understood that voltage stability is one of the main problems of power systems [3]. Decreasing the voltage values below the critical values disturbs the voltage stability. As a result, transmission lines, generators and loads can be disabled [4]. Voltage instability or more advanced voltage collapse is considered to be a dynamic phenomenon [5]. Despite the dynamic nature of voltage stability, many of its analyzes are made using static analysis methods. The problem of voltage stability occurs when power systems are overloaded, broken down, or when reactive power is inadequate. Analysis of this stability can be demonstrated by analysis of generation, transmission, and reactive consumption. Keeping the voltage at a certain value is a situation that concerns the whole power system, although the power system occurs in one region [6].

This study has been applied to the 6 bus test system of IEEE and various results have been obtained. In the analyzes, the power coefficients of the load, the length of the transmission line, the change of the mains voltages and the effects of the system shunt compensation were investigated. The simulations of the analyzes were carried out with the Power Systems Analysis Program (PSAT). Power systems were created under different operating conditions in the study. For each case, the critical values that determine the operating limits of the system have been reached by performing the load flow and the continuous load flow.

2. Material and Method

2.1. Load Flow and Continuous Load flow

You have information about the current state of the system with the load flow in the power system. As a result of the load flow, it is possible to determine the voltage amplitude and angle values of all the buses, the active and reactive powers flowing on the transmission lines, the losses on the lines. Power expressions used in power flow studies are nonlinear equations. Therefore, two different approaches are used to solve these equations. One is Gauss-Seidel and the other is Newton-Raphson algorithms [7]. In the Newton-Raphson algorithm used for load flow analysis, a series of nonlinear mathematical equations are expressed by Eq.(1).

$$f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ \cdots\cdots\cdots \\ \cdots\cdots\cdots \\ f_n(x) \end{bmatrix} = y \tag{1}$$

The solution for x, which is variable in this equation set, is sought. The Newton-Raphson algorithm equation is used to solve this equation.

$$x(i+1) = x(i) + J^{-1}[y - f\{x(i)\}] \tag{2}$$

The Newton-Raphson algorithm given in Eq.(2) is the J Jacobian matrix and vice versa. When this form is applied to the load flow, the x vector expressed in Eq.(2) is the δ angle values of all bars except the swing bar and the voltage values of all load bars. y is the active and reactive power equations used in the load flow. These expressions are shown in Eq.(3).

$$x = \begin{bmatrix} \delta \\ V \end{bmatrix} \qquad\qquad y = \begin{bmatrix} P \\ Q \end{bmatrix} \tag{3}$$

These load-flow operations are incrementally maintained until the Newton-Raphson algorithm diverges. The reason for the divergence is that it is approaching the critical voltage point [8]. The point to which the divergence is made expresses the critical values for the system or for that bus. The voltage is expressed as the critical bus voltage, the angle, the critical bus angle, and the critical bus power. In other words, critical values are determined for the voltage stability of the bus.

Continuous load flow analysis is an algorithm that iteratively processes estimation and correction functions. The basic principle behind the continuous load flow technique is based on the estimation correction step. As shown in Fig. 1, the estimation step is performed along the tangential direction at the current operating point. As a correction vector, a plane perpendicular to the tangential direction is used [9]. The load value is assumed to be constant when these operations are performed. It also has the ability to automatically change the voltage to adverse conditions that would result from the singular resolution state of the system equations.

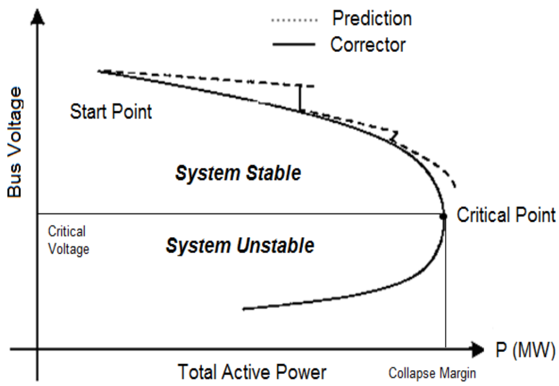

Figure 1. Predictive and corrective errors on the P-V curve

The graphs in which voltage stability is most easily observed are P-V curves obtained from the load bus. These values are expressed as critical bus voltage values. At this moment, active power is expressed as critical power value. As the voltage value decreases, the system becomes difficult to operate [10]. Voltage instability and the resulting events are a dynamic process. However, system and voltage stability are investigated with static analysis methods as well as dynamic events [11]. The relationship between the voltage-loading parameter (V-λ) of the power system and the bus, active and reactive power values is expressed in Eq.(4).

$$P_L = P_{L0}\,(1+\lambda)$$
$$Q_L = Q_{L0}\,(1+\lambda) \quad (4)$$

The P_{L0} and Q_{L0} values expressed in the equations are the initial active power and reactive power values. P_L and Q_L are the active power and reactive power values of the load. λ is the maximum load parameter value. In order to establish the relationship between the voltage and the maximum load parameter (V-λ), a continuous charge flow in the power system is required.

3. Simulation Study

This study has been applied to the 6-bar test system in Fig.2. The total load of the system is 280 MW and 190 MVAr and these powers are provided by three generators. There are also three load buses in the system. In the simulation, inductive, capacitive and capacitive loads are connected to the load buses separately. In the other case, the line length of the entire system has been changed. In the case of another operation, the line head voltages were changed. Finally, shunt compensation is connected to the load buses. The critical values of the power system were investigated by performing load flow and continuous load flow in each operating state of the system. The simulation was carried out with the Power Systems Analysis Program (PSAT) [12].

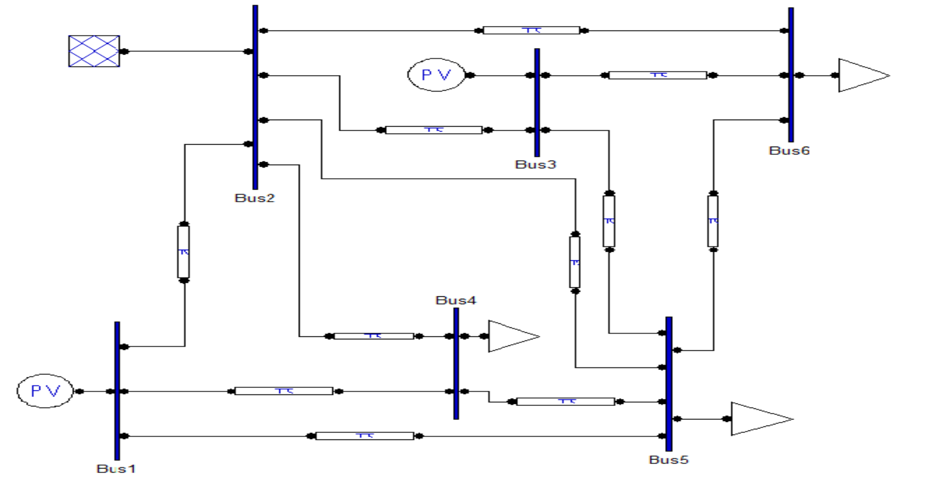

Figure 2. Simulation Study 6-bus test system.

3.1. Effect on Critical Values in Power System

It is possible to clearly see the effects of certain magnitudes in the power equations when determining the stability limits or critical values in the power system. These effects can be gathered in the main groups as effects of the power factor, effect of line length, effect of line head voltage and effects of shunt compensation [1]. These effects should be examined in detail in terms of voltage stability. The effects on the critical values of the power system of the different cases mentioned in this study were investigated by P-V curves with continuous load flow.

- Effect of Power Factor

In 6-bus system, normal and critical values of power system are obtained when inductive, ohmic and capacitive load are connected as load.

Table 1. The values obtained as a result of the load flow of the various power coefficients

Load Power Factor	Bus	Voltage (pu)	Angle (Degree)	ActivePower Losses (pu)	Reactive Power Losses (pu)
Inductive Load Cosφ=0.83	4	0.985	-2.32	0.098	-0.232
	5	0.968	-4.16		
	6	0.990	-4.21		
Ohmic Load Cosφ=0	4	1.021	-3.21	0.068	-0.352
	5	1.025	-5.10		
	6	1.031	-4.66		
Capacitive Load Cosφ=-0.83	4	0.973	-0.08	0.099	-0.226
	5	0.950	-1.05		
	6	0.976	-1.43		

The voltage amplitude values of the load buses are found by increasing the power of the load bus by gradually increasing the phase angle of the load, $\varphi=34^0$, $\varphi=0^0$, $\varphi=-34^0$ or the power factor is kept constant at 0.83, 0, -0.83. P-V curves are obtained as these values are displayed on a curve. The values obtained from the results of the load flow are given in Table 1 and the values obtained from the continuous load flow are given in Table 2.

It is seen that the voltage values of the load buses in the load flow result are within the limit values. Active and reactive losses are similar. However, negative excursions of reactive losses show that the capacitive effect of the line is greater than inductive losses.

Table 2. The values obtained by continuous power flow of various power coefficients

Load Power Factor	Bus	Voltage (pu)	Angle (Degree)	Max. Load Par. λ (pu)	Active Power Losses (pu)	Reactive Power Losses (pu)
Inductive Load Cosφ=0.83	4	0.536	-16.20	11.164	2.476	6.380
	5	0.733	-12.03			
	6	0.830	-13.98			
Ohmic Load Cosφ=0	4	0.548	-19.29	12.952	2.488	6.379
	5	0.791	-13.55			
	6	0.871	-15.14			
Capacitive Load Cosφ=-0.83	4	0.526	-12.51	10.957	2.414	6.202
	5	0.715	-7.96			
	6	0.823	-10.62			

Continuous load flow by connecting inductance, ohmic and capacitive load to the power system resulted in critical values. When these obtained values are plotted on P-V curves, the curves in Figure 3 are obtained.

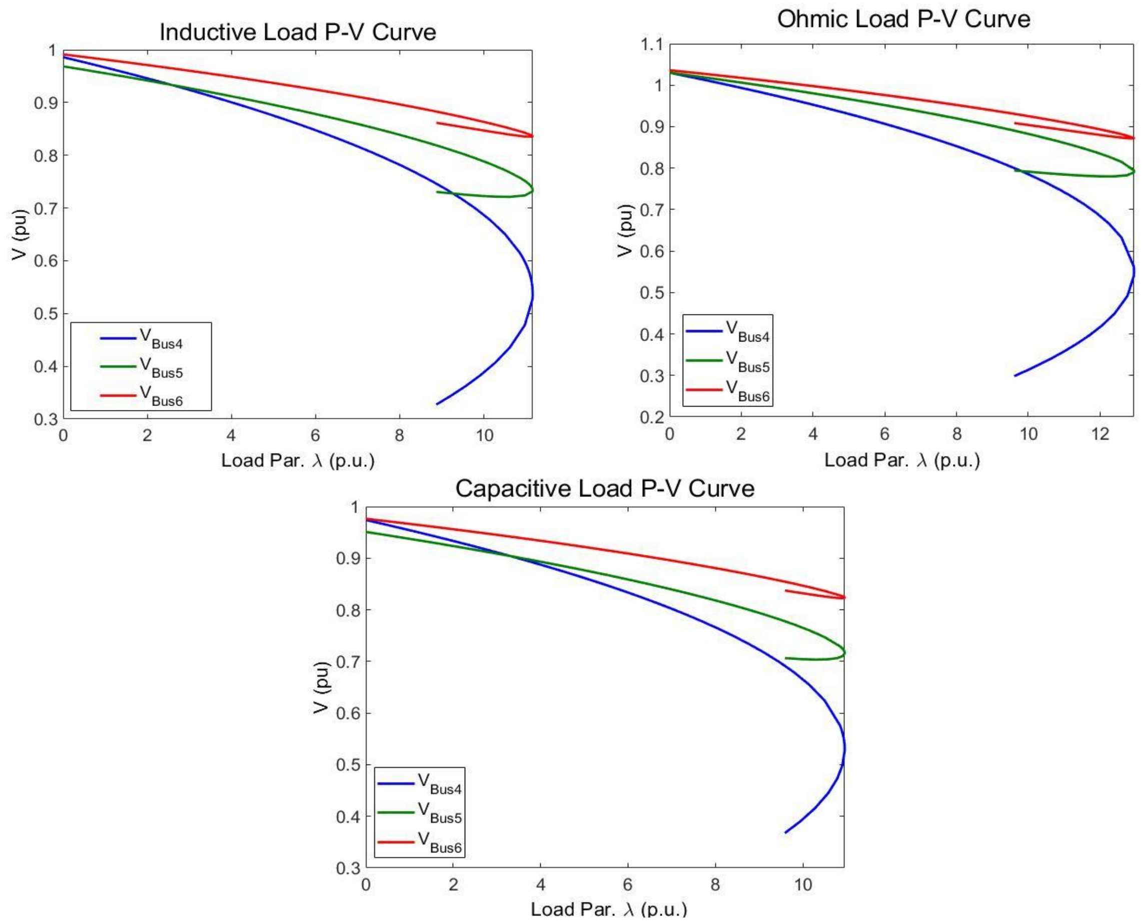

Figure 3. P-V Curves Obtained at Different Loads

In the P-V curves obtained as a result of the continuous load flow, the critical voltage values of all load types were found to be similar, but the maximum load capacity of the load was observed to be higher than the other loads. At all loads in terms of critical voltage, 4th bus 0.5pu with the most stable, the 6th bus is 0.8pu with the most unstable bus.

- Effect of Line Length

It is not possible later to change the critical values of the system by changing the line length in terms of stability. For this reason, in the design phase of the power system, especially in route selection, the effect of the line length on the critical values must be examined. Since the ohmic and inductive reactance of the transmission line is given as ohm / km and the susceptance is S / km (if the conductor is neglected), changing the length of the transmission line causes the parameters of the line to change.

Table 3. Values obtained as a result of load flow at various line lengths

Line length	Bus	Voltage (pu)	Angle (degree)	Active Power Losses (pu)	Reactive Power Losses (pu)
Short Line (*l/2*) Cosφ=0.83(end)	4	0.985	-2.32	0.098	-0.232
	5	0.968	-4.16		
	6	0.991	-4.21		
Midline (*l*) Cosφ=0.83(end)	4	0.915	-5.34	0.221	-0.312
	5	0.879	-9.71		
	6	0.927	-9.46		
Long Line (*1,5.l*) Cosφ=0.83(end)	4	0.816	-9.48	0.436	0.006
	5	0.737	-18.10		
	6	0.837	-16.88		

Depending on the change of these parameters, the P-V curve and therefore the critical values in the power system, also change. Voltage, angle, losses and maximum load values obtained from the results of the load flow and the continuous load flow depending on the various line lengths are given in Tables 3 and 4.

Table 4. Values obtained as a result of continuous load flow at various line lengths

Line length	Bus	Voltage (pu)	Angle degree)	Max. Load Par. λ (pu)	Active Power Losses (pu)	Reactive Power Losses (pu)
Short Line (*l/2*) Cosφ=0.83(end)	4	0.535	-16.20	11.153	2.476	6.380
	5	0.733	-12.03			
	6	0.835	-13.98			
Midline (*l*) Cosφ=0.83(end)	4	0.525	-17.45	3.597	1.521	3.513
	5	0.623	-19.31			
	6	0.779	-19.08			
Long Line (*1,5.l*) Cosφ=0.83(end)	4	0.697	-12.88	0.620	0.871	1.438
	5	0.551	-25.25			
	6	0.754	-22.40			

While the voltage values of the short and medium-length lines remain at the normal limit as a result of the load flow, the voltage values of 0.8-0.7pu have been realized due to the active losses in the long transmission line. Losses increase in proportion to length. In the continuous load flow, the short line can be loaded the most, while the long transmission line can be loaded at least. Here, the system operates under constant power coefficient of cosφ=0.83 (end) and the P-V curves of three different length lines are shown in Figure 4.

The P-V curves reveal an unfavorable situation in terms of the stability of the voltage depending on the increase of the line length as seen from the results obtained. It is observed that the amount of power that can be transported decreases depending on the extension of the transmission line. The shortening of energy transmission lines is more stable in terms of voltage stability.

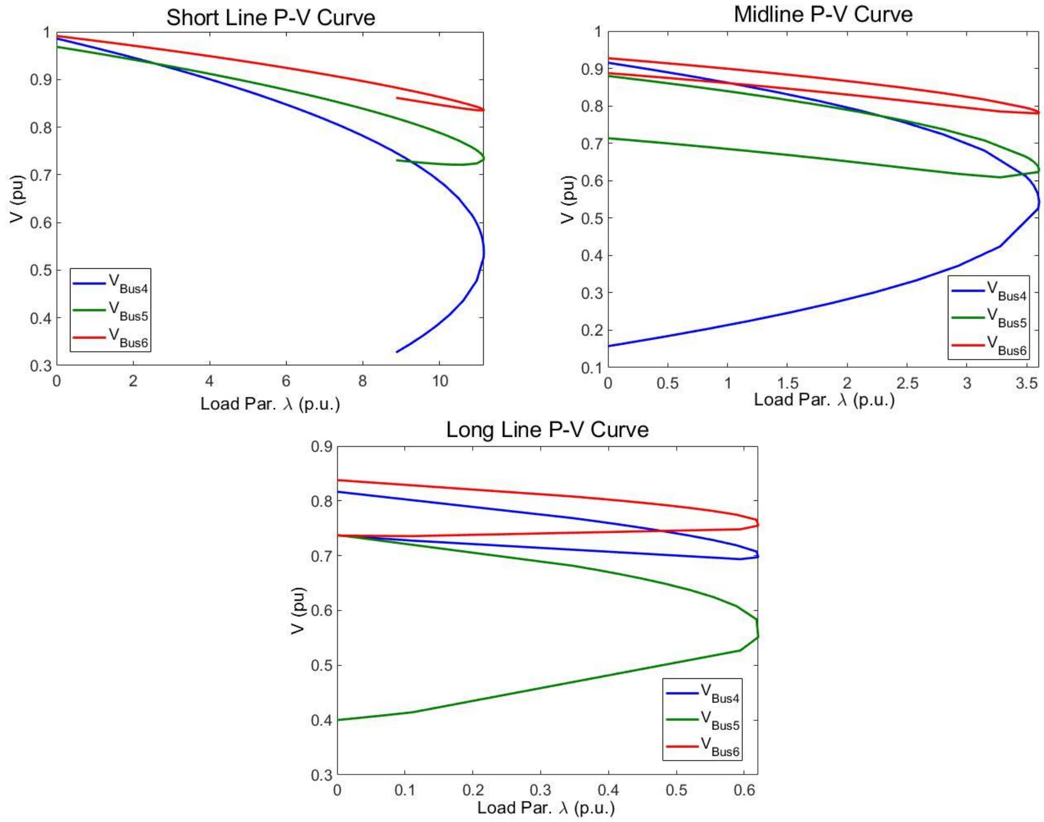

Figure 4. P-V Curves Obtained on Different Line Lengths

- Effect of Input Voltage

Using the data of the sample system, the change of the stability values of the power system was investigated as the line input voltage increased and decreased by 10% steps. The values of voltage, angle, losses and maximum load obtained from the results of the load flow and the continuous load flow at various input voltages are given in Tables 5 and 6.

Table 5. Values obtained as a result of the load flow in the Change of Line Input Voltage

Line Input Voltage	Bus	Voltage (pu)	Angle (degree)	Active Power Losses (pu)	Reactive Power Losses (pu)
	4	0.746	-0.43		
0,9 pu	5	0.691	-3.01	0.267	0.286
	6	0.752	-3.83		
	4	0.873	-0.30		
1 pu	5	0.832	-2.18	0.183	-0.118
	6	0.877	-2.77		
	4	0.991	-0.25		
1,1 pu	5	0.960	-1.73	0.134	-0.433
	6	0.995	-2.15		

If there is a drop in voltage as a result of voltage instability for any reason in the system, the magnitude of line input voltage can be increased by increasing the line end voltage. In this case, if it is assumed that the active power value of the line is not changed, the voltage of the load bus at the end of the line will be further reduced as seen from the P-V curve in Figure5. This is the conclusion that the under load tap changer transformer cause the line end voltage to decrease further in case of increasing the voltage in case of decrease of voltage. When the power system is exposed to a fast-changing disruptive effect, the slower response of the tap changers is insufficient to maintain the voltage stability [13,14].

Table 6. Values obtained as a result of continuous load flow in Change of Line Input Voltage

Line Input Voltage	Bus	Voltage (pu)	Angle (degree)	Max. Load Par. λ (pu)	Active Power Losses (pu)	Reactive Power Losses (pu)
0,9 pu	4	0.456	-8.67	3.047	1.451	3.708
	5	0.459	-10.75			
	6	0.630	-12.28			
1 pu	4	0.500	-10.32	4.929	1.598	3.933
	5	0.601	-9.15			
	6	0.740	-11.29			
1,1 pu	4	0.417	-374.80	6.809	2.448	5.886
	5	0.697	-9.14			
	6	0.848	-10.69			

It is seen from the P-V curves given in Figure 5 that the increase in line input voltage causes the critical values to increase.

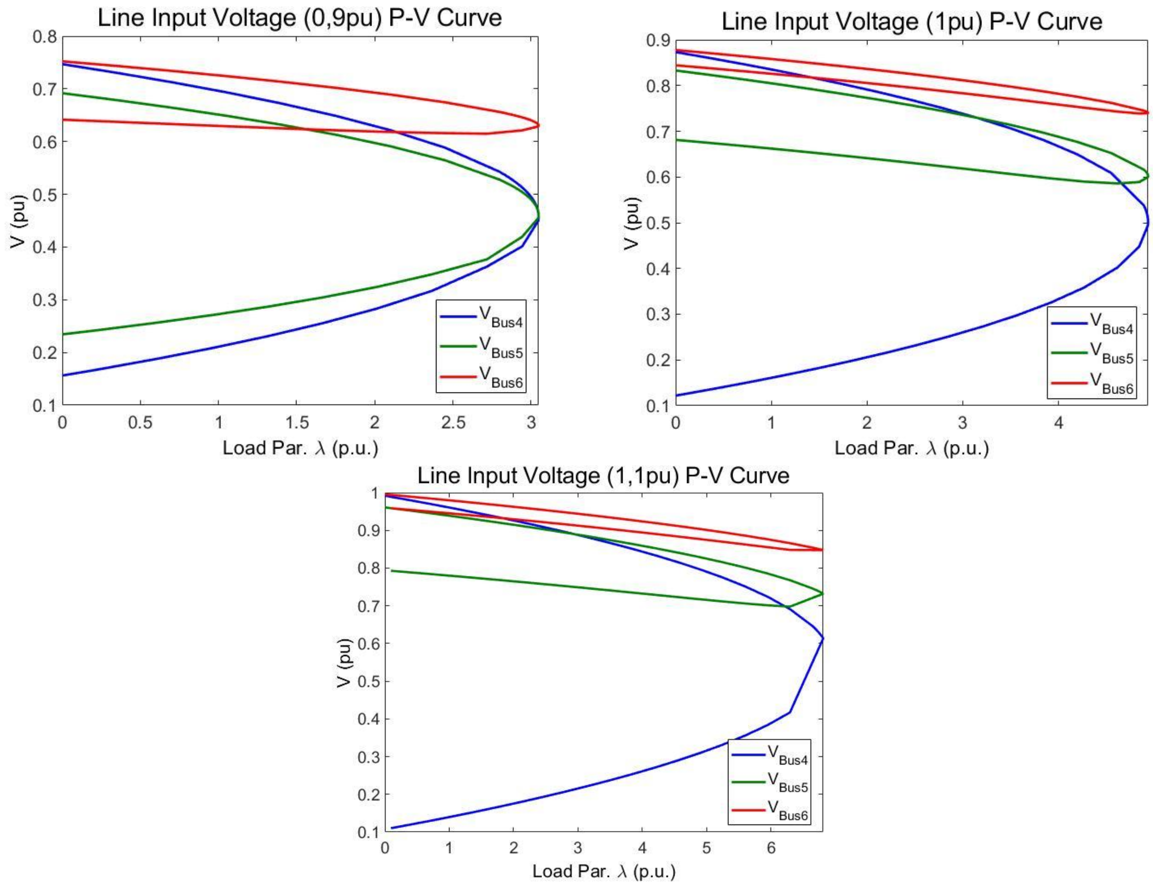

Figure 5. P-V Curves Obtained at Different Line Input Voltages

- Effect of Shunt Compensation

Where shunt compensation is not considered in a power system, the load-carrying voltage of the idle transmission line is at its steady state maximum. If there is not sufficient compensation, the capacitive currents flowing from the line and system will cause overvoltage in the devices connected to the system. Therefore, shunt reactors should be installed at appropriate locations. These reactors are usually connected directly to the phase neutral at the end of the transmission line

[15]. The shunt reactors are reduced in the transmission line y constant by the shunt compensation ratio.

$$Yy = (1 - K_d) \times Y \tag{5}$$

The shunt compensation ratio *(K_d)* is expressed as a percentage. The variation of P-V curves for different shunt compensation percentages is shown Tables 7 and 8 and in Figure 6

Table 7. Values obtained as a result of load flow in case of shunt compensation

Shunt Compensation Ratio	Bus	Voltage (pu)	Angle (degree)	Active Power Losses (pu)	Reactive Power Losses (pu)
	4	0.933	-0.27		
Kd=0	5	0.897	-1.93	0.156	-0.282
	6	0.937	-2.42		
	4	1.060	-2.83		
Kd=1,0	5	1.063	-4.42	0.059	-0.679
	6	1.066	-3.75		

Table 8. Values obtained as a result of continuous load flow in case of shunt compensation

Shunt Compensation Ratio	Bus	Voltage (pu)	Angle (degree)	Max. Load Par. λ (pu)	Active Power Losses (pu)	Reactive Power Losses (pu)
	4	0.525	-10.90			
Kd=0	5	0.658	-8.80	5.912	1.711	4.161
	6	0.790	-11.07			
	4	0.587	-12.35			
Kd=1.0	5	0.787	-9.69	7.117	1.337	3.031
	6	0.892	-11.49			

According to this, although shunt compensation is performed on the transmission line, it is observed that the limits of voltage stability are reduced even though it prevents the voltage increases at the end of the line. It is also determined that the power to be withdrawn from the system increases when shunt compensation is performed.

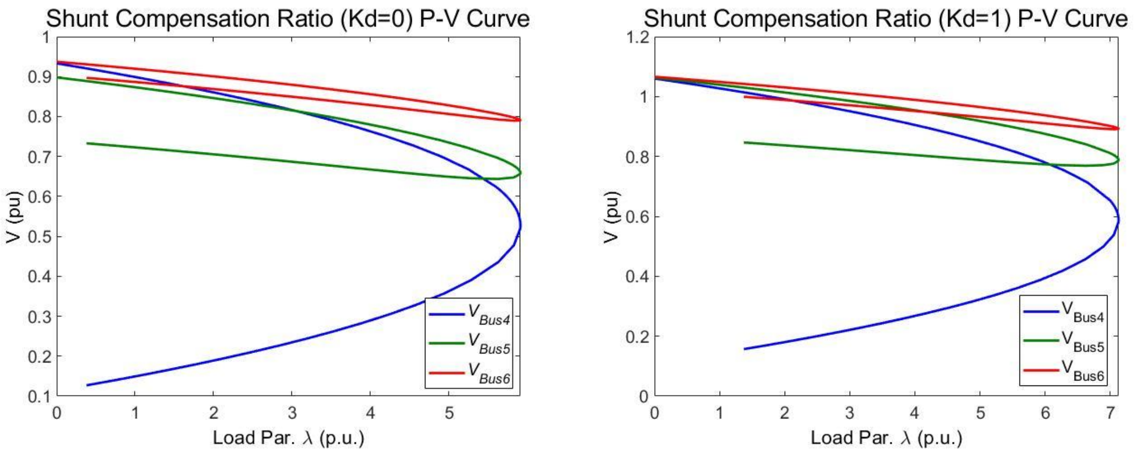

Figure 6. P-V Curves Obtained in Different Shunt Compensation Values

5. Results

In this study, the 6-bar test system was run separately under different operating conditions. Power system; by varying the power coefficient of the load, by changing the length of the transmission line, by changing the values of the line input voltage and by shunt compensation to the load bus. For each case, Newton-Raphson (NR) load flow was performed in the system to determine the normal operating voltage and load values of the system. Then the continuous flow of charge is made to reach the point where the power flow equation solutions are singular, and the critical bara values of the system are obtained.

As a result of the analysis; the voltage values and the angle values of the load buses have been found to be within the stability limits of the system under all conditions and during normal operation. According to different loads; the maximum power can be carried by the Ohmic load, and the 4th busbar is the most stable bus and the 6th bus is the most unstable bus.

Depending on the line length; maximum power transfer can be performed with short line, and minimum power transfer can be performed with long line. In addition, the short line has been the most stable in terms of voltage stability in terms of voltage.
In terms of line input voltage; although the amount of power that can be transported increases as the voltage increases, the voltage stability deteriorates. When the shunt capacity was examined, it was observed that the voltage amplitude values decreased while the shunt capacity increased.

References

[1]. Yalçın, M.A., "Enerji İletim Sistemlerinde Gerilim Kararlılığının Yeni Bir Yaklaşım ile İncelenmesi", Doktora Tezi, İ.T.Ü., F.B.E., 1995

[2]. Taylor C.W., "Power System Voltage Stability", Mc Graw-Hill, Inc., 1994

[3]. Johansson, S., "Long-Term Voltage Stability in Power Systems Alleviating the Impact of Generator Current Limiters", Doctoral Thesis, Technical Report No 235, Department of Electric Power Engineering School of Electrical and Computer Engineering, Chalmers University of Technology, 1998

[4]. Glavic, M., "Power Sytem Voltage Stability A Short Tutorial", University of Liege, Electrical Engineering and Computer Science Department, 2003

[5]. Van Cutsem, T., Vournas, C.D., "Voltage Stability of Electric Power Systems", Kluwer Academic Publishers, 1998

[6]. Repo, S., "On-Line Voltage Stability Assesment of Power System an Approach of Black-Box Modelling", Phd. Thesis, Tampera University of Technology, Publication 344, Tampera, 2001

[7]. Glover, J.D., Sarma, M.S., "Power System Analysis and Design", 3rd ed., Brooks/Cole, 2001

[8]. Ajjarapu, V., Chrısty, C., "The Continuation Power Flow: A Tool for Steady State Voltage Stability Analysis", IEEE Transaction on Power Apparatus and Systems, Vol. 7, No.1, p.416–423, 1992

[9]. Canizares, Claudio A., and Fernando L. Alvarado, Point of collapse and continuation methods for large AC/DC systems, IEEE transactions on Power Systems 8.1 (1993): 1-8.

[10]. Kundur, P., "Power System Stability and Control", New York: McGraw-Hill, 1994

[11]. Kundur, P., and G.K., Morıson, "A review of definations and classification of stability problems in today's power systems", Panel Sension on Stability Terms and Definations, IEEE PES Winter Meeting, New York, 1997

[12]. Milano, F., Power System Analysis Toolbox Quick Reference Manual for PSAT version 2.1.2, 2008

[13]. Abe, S., Fukunova, Y., Isono, A., Kondo, B., "Power System Voltage Stability" IEEE Transaction on Power Apparatus and Systems, Vol. 101, No.10, p.3830–3840, 1982

[14]. Ohtskı, H., Yokoyama, A., Sekıne, Y., "Reverse Action of on-Load Tap Changer in Association with Voltage Collapse ", Vol.6, No.1, pp. 300–306, 1991

[15]. Miller, T.J.E., "Reactive Power Control in Electric Power System ", John Wiley&Sons, Inc., 1982.