A Graphical User Interface (GUI) Approach of Voltage Instability Analysis Based on P-V and Q-V Curves in Radial Power System Networks

Marizan Sulaiman [1], Noor Ropidah Bujal [2] and Rosli Omar [3]

[1,3] Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Malaysia

[2] Depart of Electrical Engineering, Merlimau Melaka Polytechnic, Malaysia

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Abstract— Voltage instability analysis is an important aspect in power system equilibrium. This paper presents the voltage instability analysis of power system at radial distribution and transmission feeders. The voltage instability analysis is carried out on a single feeder comprising two-bus system using ABCD line parameters. The feeder's voltage at distribution and transmission systems has been monitored for lagging and leading load conditions at different power factors. The active power-voltage (P-V) and reactive power-voltage (Q-V) curves are used to monitor the voltage instability analysis of the feeders using Graphical User Interface (GUI) based on MATLAB. The P-V and Q-V curves are plotted with improved accuracy in the MATLAB application software. The voltage at critical point, voltage regulation, voltage gap and line currents at feeders are measured and displayed on GUI for each lagging and leading load power factor. The voltage instability analysis incorporates the MATLAB based GUI for user friendly environment suitable for teaching, learning and training applications and this software package is targeted for engineering students and practicing engineers.

Keywords: GUI, Voltage Instability; P-V and Q-V Curves; Radial Power Networks.

1. INTRODUCTION

Power system stability is an ability of electric power system to regain a state of operating equilibrium after being subjected to a disturbance [1-2]. There are three classes of power system stability, namely rotor angle stability, frequency stability and voltage stability [2-4]. Voltage stability is in respect of the ability of a power system to maintain steady voltage at all busses in the system under normal condition and after being subjected to a disturbance [6]. However, voltage instability may occur either when voltage fall or rises at some busses. Therefore, the voltage instability analysis should be implemented to monitor the voltage stability at voltage feeder and improves the power system stability.

The quantity of power transmitted is based on power factor and ABCD line parameters [7,8,11]. The load condition at transmission feeder will affect the transmission line performance in terms of voltage critical, voltage gap, and voltage regulation and transmission line current. P-V curve and Q-V curve are widely used to monitor the voltage stability of

Distribution and transmission feeder [5,10]. Therefore, in this study, PV and QV curve for various power factors are used as a tool for analysing voltage stability. Fig. 1 shows a single feeder comprising of two-bus system using ABCD line parameters.

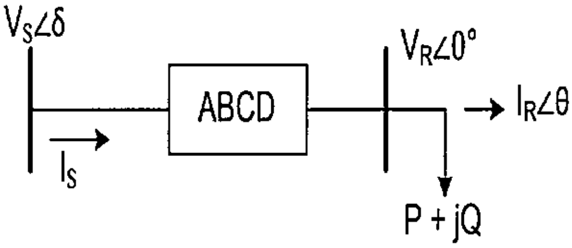

Fig. 1. Single feeder of two-bus system with ABCD constants.

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2. THEORETICAL BACKGROUND

There are three types of transmission line and they are differentiated by the length of the line and their operating voltage. Standard operating voltages in Malaysia are 11kV, 22kV, 33kV, 132kV, 275kV and 500kV [9].The design and operation of transmission lines are greatly influenced by the voltage drop, line losses and efficiency of the transmission system. All these factors related to transmission system are dependent on the line parameters, for example, the resistance (R), inductance (L) and capacitance (C) of the transmission line. Parameters R, L and C associated with any transmission line are distributed uniformly along the length of the line [3,4,8 [1]].

A: Short-length Transmission Line

In Malaysia, the short-length transmission line (distribution system) always refers to the line that is less than 80km [8][2]. It is operated at 11kV, 22kV or 33kV. In short-length transmission line, only resistance (R) and inductance (L) are considered while capacitance (C) is neglected due to shorter distance and lower operating voltage. Figure 2 shows the model of the short length transmission line and the transmission line can be presented in two-port network representation as shown in Fig 3.

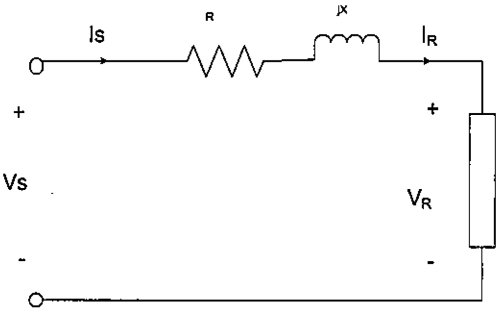

Fig. 2. Short-length transmission line equivalent circuit

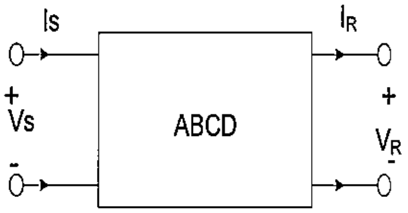

Fig. 3. Two-port network representation of transmission line

In matrix form, the constant ABCD parameters are;

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} \qquad (1)$$

And the determinant of matrix (1.0) is

$$AD - BC = 1 \qquad (2)$$

Where

$A = 1$ $B = Z$ $C = 0$ $D = 1$

Receiving end voltage per phase is

$$V_{R_{1ph}} = \frac{V_{R3\phi}}{\sqrt{3}} \angle 0° \qquad (3)$$

From the calculated sending end voltage (Vs) and sending end current (Is), sending end apparent power can be obtained by using;

$$S_{S(3\phi)} = 3V_S I_S{}^* \qquad (4)$$

$$P_S = \sqrt{3} V_S I_S \cos(\theta V_S - \theta I_S) \qquad (5)$$

$$Q_S = \sqrt{3} V_S I_S \sin(\theta V_S - \theta I_S) \qquad (6)$$

$$P_R = \sqrt{3} V_R I_R \cos(\theta V_R - \theta I_R) \qquad (7)$$

$$Q_R = \sqrt{3} V_R I_R \sin(\theta V_R - \theta I_R) \qquad (8)$$

$$I_R = \frac{P_{R\max}}{\sqrt{3}(V_{\text{rated}})(\cos\phi)} \qquad (9)$$

Voltage regulation is defined as the percentage change in voltage at receiving end of the line in going from no-load (V_{RNL}) to full-load (V_{RFL}).

$$\% V_{Reg} = \frac{|V_{R(NL)}| - |V_{R(FL)}|}{|V_{R(FL)}|} x100 \qquad (10)$$

At no load, for short-length transmission line, $I_R = 0$ and [3,4,8]

$$V_{R(NL)} = \frac{V_S}{A} \qquad (11)$$

and

$$A = 1 \text{ and } V_{RNL} = Vs \qquad (12)$$

B: Medium-length Transmission Line

The distance of medium-length transmission line is between 80 km to 250 km with operating voltage are 132kV, 275kV and 500kV [8]. Medium-length transmission line is normally analysed using nominal-π model. Figure 4 shows the equivalent circuit of medium-length transmission line.

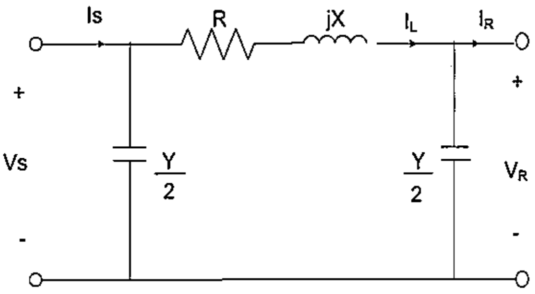

Fig. 4. Medium-length transmission line equivalent circuit

The ABCD constant for nominal π model are given by

$$\begin{aligned} A &= 1+\frac{ZY}{2} \\ B &= Z \\ C &= Y\left(1+\frac{ZY}{4}\right) \\ D &= 1+\frac{ZY}{2} \end{aligned} \qquad (13)$$

For a nominal-π circuit, general circuit parameter n matrix form is,

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} 1+\frac{ZY}{2} & Z \\ \left(Y+\frac{Y^2Z}{4}\right) & 1+\frac{ZY}{2} \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} \qquad (14)$$

From the calculated sending end voltage (Vs) and sending end current (Is), sending end apparent power, reactive power, active power and sending-end current can be obtained by using Eqns. (4), (5), and (6). While receiving-end reactive power, active power and receiving-end current can be obtained by using Eqns. (7), (8) and (9). Voltage regulation for a medium line becomes;

$$\%\ V_{Reg} = \frac{\left|\frac{V_S}{A}\right| - \left|V_{R(FL)}\right|}{\left|V_{R(FL)}\right|} x100 \quad (15)$$

3. P-V AND Q-V ALGORITHMS

In this paper the algorithm is divided into three parts for convenience. The flowchart [5] is shown in Fig 5.

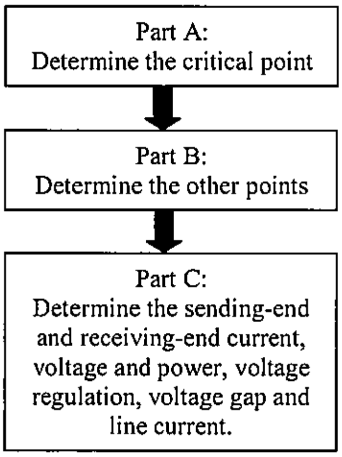

Fig. 5. Flowcharts of P-V and Q-V algorithms

Fig 6 shows the P-V and Q-V curves that should be plotted by using the algorithm [1-10].

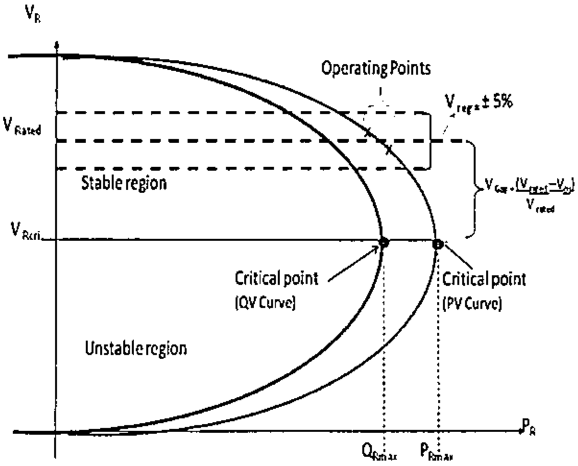

Fig. 6. P-V and Q-V curves

***Part A** Determine the Critical Point*

The calculation of part A is starting from converting the power factor angle, phi (ϕ) into degree (°) by using Eqn. (15) if the given power factor is in radian. The critical point is calculated as;

i. Determine power factor angle.

$$\cos\phi = \text{p.f}$$

$$\phi = \cos^{-1}(p.f) \qquad (16)$$

ii. Using the power factor angle, calculate the phi prime, ϕ' using;

$$\phi' = 180° - (\beta - \alpha) + \phi \qquad (17)$$

iii. Determine the receiving-end apparent power, S_{Rmax}, receiving-end power, P_{Rmax}, reactive power, Q_{Rmax} and receiving end voltage at a critical point, V_{Rcri}.

$$S_{R\max} = \frac{V_{rated}^{\ 2}}{4AB\sin^2\left(\frac{\phi'}{2}\right)} \qquad (18)$$

$$P_{Rmax} = S_{Rmax}\cos\phi \qquad (19)$$

$$Q_{R\max} = S_{Rmax}\sin\phi \qquad (20)$$

$$V_{Rcri\,3phase} = \frac{Vrated}{2A\sin\left(\frac{\phi'}{2}\right)} \qquad (21)$$

$$V_{Rcri\,1phase} = \frac{V_{Rcri\,3phase}}{\sqrt{3}} \qquad (22)$$

iv.Then, calculate the prime critical power angle, δ'_{cri} and the critical power angle, δ_{cri}

$$\delta'_{cri} = 90° - \frac{\phi'}{2} \qquad (23)$$

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$$\delta_{cri} = \delta'_{cri} + \alpha \tag{24}$$

***Part B* Calculation of the Other Points**

Part B is calculation of other points at P-V and Q-V curves. The first step is to determine the delta prime δ' which is Δδ ± 2°. The range of Δδ is from 2° to 30° for δ'_1 and from -2° to -30° for δ'_2. The calculation of part B is given as;

i. Calculate the delta prime, δ'_1 and δ'_2

$$\delta'_1 = \delta' cr_1 + \Delta\delta$$

$$\delta'_2 = \delta' cr_2 - \Delta\delta \tag{25}$$

ii. Then calculate the receiving-end apparent power, S_{R1} and S_{R2}

$$S_{R1} = \frac{V_{rated}^2 \sin(\phi' + \delta'_1)\sin\delta'_1}{AB\sin^2\phi'}$$

$$S_{R2} = \frac{V_{rated}^2 \sin(\phi' + \delta'_2)\sin\delta'_2}{AB\sin^2\phi'} \tag{26}$$

iii. By using the value of S_{R1} and S_{R2}, determine the receiving-end real power, P_{R1}, P_{R2}, Q_{R1} and Q_{R2}.

$$P_{R1} = S_{R1}\cos\phi$$

$$P_{R2} = S_{R2}\cos\phi \tag{27}$$

$$Q_{R1} = S_{R1}\sin\phi$$

$$Q_{R2} = S_{R2}\sin\phi \tag{28}$$

iv. The last step is determine the receiving-end voltage, V_{R1} and V_{R2}.

$$V_{R1} = \frac{V_{rated}\sin(\phi' + \delta'_1)}{A\sin\phi'} \tag{29}$$

$$V_{R2} = \frac{V_{rated}\sin(\phi' + \delta'_2)}{A\sin\phi'} \tag{30}$$

***Part C* Determine Sending-end and Receiving-end Current, Voltage and Power, Voltage Regulation, Voltage Gap and Line Efficiency**

Part C calculations consists of determination of receiving and sending end data value, voltage regulation, line current and voltage gap by using (9) and (10). Voltage Gap between rated voltage and Critical Point is calculated using; (31)

4. GUI DESIGN FEATURES

$$V_{gap} = \frac{V_{rated} - V_{cri}}{V_{rated}} x100\%$$

By using the MATLAB programming, each point of P-V and Q-V curves based on the power factor angle entered by the user can be calculated. Then, the P-V and Q-V curves will be displayed on the GUI page as well as all data of each calculated data value. The flowchart of the procedure is shown in Figure 7 [12-15-16]. The program starts by showing the designed GUI page as shown in Figure 8. There are nine panels in the GUI page. The first panel is the types of transmission line selection where the users are given two options either short-length transmission line (distribution system) or medium-length transmission line. Fig 9 shows the types of transmission line panel.

The second panel is the power factor angle where users are required to enter the power factor angle in degrees. In order to plot P-V and Q-V curves, the power factor angle is considered positive for lagging power factor and negative for leading power factor. The unity power factor is fixed to 0°. Therefore, the user is also required to enter the negative sign if the load condition is leading. Then the power factor angle is converted into radian by a mouse click, keyboard tab key or enter key. The value in radian will be displayed in the box. The panel's default power factor angle is set to be zero (unity) and the user can enter the other value by replacing the value. The default values are shown in Fig 10.

The third panel is load condition where as users are given three options, either lagging load, leading load or unity as shown in Figure 11. If leading load condition is selected, a negative sign will automatically appear before the power factor angle. The fourth panel is for declaring the line rated voltage and line parameters in terms of ABCD constants. The user is required to enter the value either in whole numbers or exponential numbers. The magnitude of constant A should be entered in the A box while the angle is defined as alpha (α). Similarly, the magnitude and angle of constant B, constant C and constant D are also should be entered into the respective boxes. The action panel contains five buttons known as "CURVE", "SAVE", "LOAD", "RESET" and "EXIT" buttons .The function of each button is described in Table 1.

The output data panel in GUI is displayed three (3) tabulated forms. Table 1 displays all the data at transmission and distribution receiving-end, while Table 2 depicts all the results of transmission and distribution sending-end. Table 3 shows the operating points that relies within the ± 5% of rated voltage. The curve panel is used to display P-V and Q-V curves that have been calculated. The P-V curve will be presented in black-star curve while Q-V curve is presented by red-square curve. The blue vertical line shows the origin of the curve and the horizontal blue line indicates the line rated voltage. The Green dashed line represents the range within ± 5 % of rated voltage and the magenta dashed line shows the band of ±10% of rated voltage. The curve data panel displays all data of every point at the P-V and Q-V curves. At the curves, critical points are labelled with left arrow so that easier to monitor the critical point of both curves and the critical point panel is used to monitor the value at critical point only. All the results will be saved into excel file to a specified folder named as "save data" folder. The folder is automatically created in the same folder where the GUI is saved and the results are saved in an excel file that is name complete with date and time of saving. For users convenience, all the saved data can be retrieved from the 'save data' folder and display all the results in the corresponding tables and figures using the "LOAD" button.

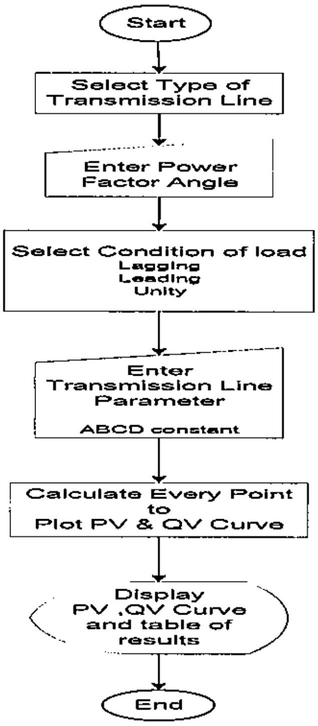


Fig. 7. Procedures in Using the GUI

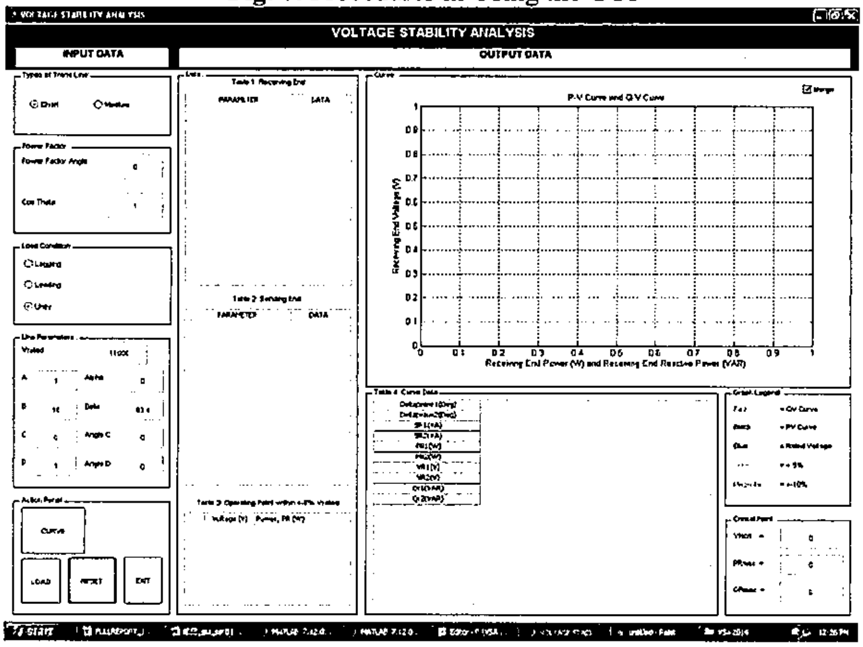
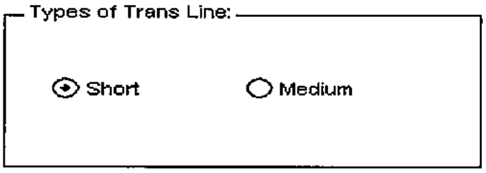


Fig. 8. GUI Page



Types of Trans Line:

◉ Short ○ Medium

Fig. 9. Types of Transmission Line Panel

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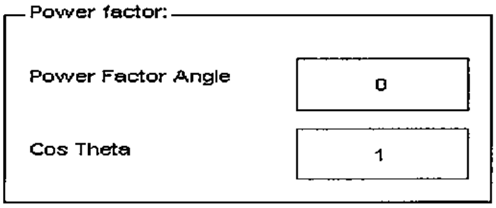
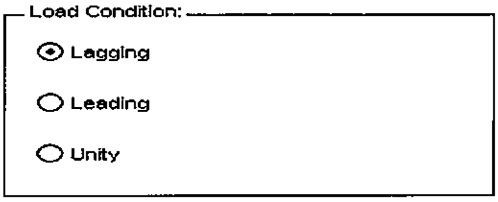


Power Factor Angle: 0

Cos Theta: 1

Fig. 10. Power Factor Panel



● Lagging

○ Leading

○ Unity

Fig. 11. Load Condition Panel

Table 1 Function of button on menu panel

No	Button	Function
1.	CURVE	To calculate and plot PV and QV curves.
2.	SAVE	To save all results from the table and carve into excel file in 'Save Data' folder.
3.	LOAD	To retrieve data from saving data folder
4.	RESET	To clear all figures at the curve's panel.
5.	EXIT	To exit the GUI window program.

5. SIMULATION AND RESULTS

The two sample case studies were chosen for simulation purposes are as follows;

Case 1: Three-phase Distribution System (Short-length Line)

For short-length transmission line (distribution system) delivers 1100 kW at 11kV at 0.8 lagging power factor, the total resistance and inductive reactance per phase of the line are 8Ω and 16Ω respectively. V_{rated} = 11kV. The short transmission line parameters are:

$$A = D = 1\angle 0^\circ \quad B = 17.89\angle 63.43^\circ\Omega \quad C = 0 \tag{32}$$

$$A = D = A\angle\alpha \quad B = B\angle\beta \quad C = C\angle AngC \tag{33}$$

Fig 12 shows the P-V and Q-V curves for short-length transmission line at very bad (0.707), unity and very good (0.95) lagging power factor. The black-star curve represents the P-V curve while the red-square curve represents the Q-V curve.

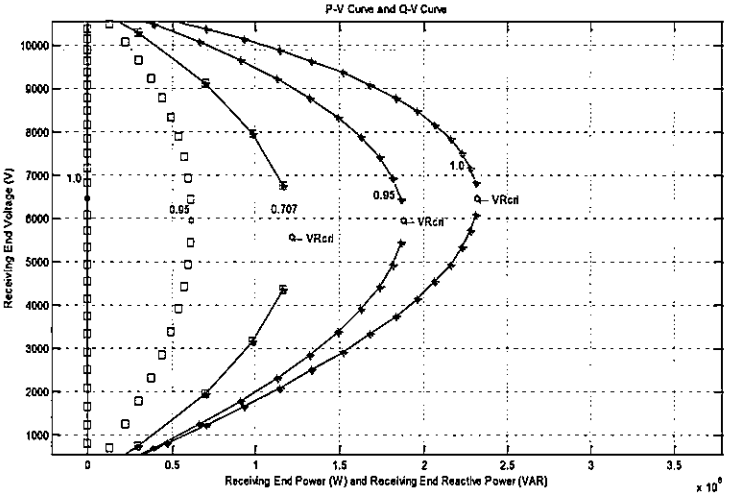


Fig. 12. P-V and Q-V Curves for Short-length Transmission Line at Very Bad (0.707), Unity (1.01) and Very Good (0.95) Lagging Power Factor

Table II shows the data at the critical point of P-V and Q-V curves for various lagging and unity power factor. From this table, the system's performance in terms of line currents, voltage regulation, and voltage gap can be monitored.

Table 2. Results of short-length transmission line at lagging and unity power factors

Power Factor	V_{cri} (kV)	P_{Rmax} (MW)	Q_{Rmax} (MVAR)	I_R (A)	Vreg (%)	Vgap (%)
0.707	5.57	1.22	1.22	90.52	24.6	49.4
0.8	5.65	1.42	1.07	93.1	24.2	48.6
0.85	5.72	1.54	0.96	95.27	23.8	48
0.9	5.81	1.69	0.82	98.41	23.3	47.2
0.95	5.96	1.87	0.62	103.49	22.5	45.8
1.0	6.46	2.32	0	121.85	19.5	33.9

The PV and QV curves for leading load condition at various power factors are shown in Figure 13.

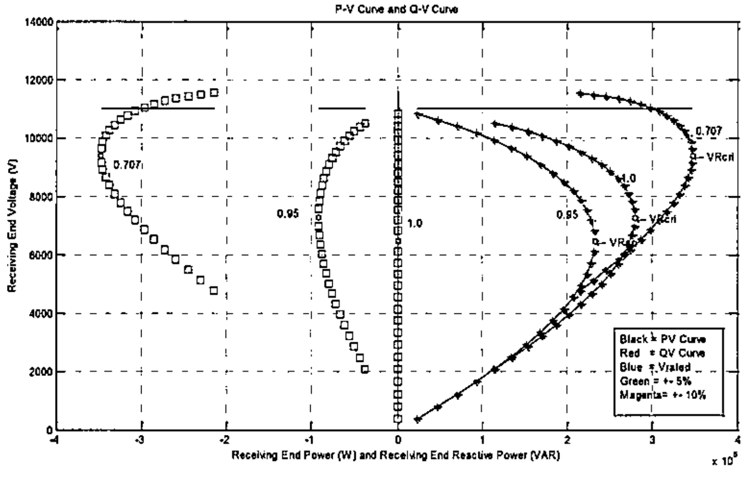


Fig.13. P-V and Q-V Curves for Short-length Transmission Line at Very Bad (0.707), Unity (1.01) and Very Good (0.95) Leading Power Factor

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Table 3 shows the data at the critical point of P-V and Q-V curve for various leading and unity power factor.

Table 3 Results of short-length transmission line at leading power factors

Power Factor	V_{cri} (kV)	P_{Rmax} (MW)	Q_{Rmax} (MVAR)	I_R (A)	Vreg (%)	Vgap (%)
0.707	9.4	3.47	-3.47	257.78	3.6	14.5
0.8	8.58	3.27	-2.46	214.82	7.4	22
0.85	8.16	3.14	-1.95	193.99	9.7	25.8
0.9	7.73	2.99	-1.45	174.10	12.1	29.8
0.95	7.27	2.79	-0.92	153.93	14.8	33.9

Case 2: Three-phase Transmission System (Medium-length Line)

A radial transmission line system with 275kV 3 phase line is being studied for medium transmission line and sending- end voltage, Vs is constant. Rated voltage is considered same as Vs. V_{rated} is considering equal to Vs [5]. The analysis is based on the following line parameters:

$$\begin{aligned} A &= D = 0.93\angle 1.5^\circ \\ B &= 115\angle 77.5^\circ \qquad (34) \\ C &= 13.07\text{x}10^{-4}\angle 92.06^\circ \end{aligned}$$

The P-V and Q-V curves for lagging load condition at various power factors are shown in Fig. 14.

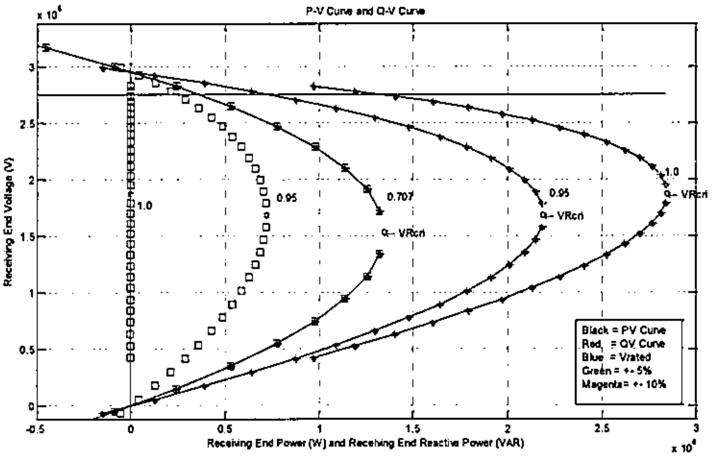

Fig. 14. P-V and Q-V Curves for Medium-length Transmission Line at Very Bad (0.707), Unity (1.01) and Very Good (0.95) Lagging Power Factors.

Table IV shows the data at the critical point of P-V and Q-V curve for various lagging power factors and unity power factor.

Power Factor	V_{cri} (kV)	P_{Rmax} (MW)	Q_{Rmax} (MVAR)	I_R (A)	Vreg (%)	Vgap (%)
0.707	153.4	134.6	134.6	399.68	27.7	44.2
0.8	156.9	159.2	119.5	417.93	26.9	42.9
0.85	159.6	175	108.5	432.33	26.3	42
0.9	163.2	194	93.9	452.42	25.5	40.6
0.95	168.9	219.1	72	484.23	24.3	38.6
1.0	187.6	284.7	0	597.68	20.1	31.8

Table. 4. Results of medium-length transmission line at lagging and unity power factors. The P-V and Q-V curves for leading load condition at various power factors are shown in Fig. 15.

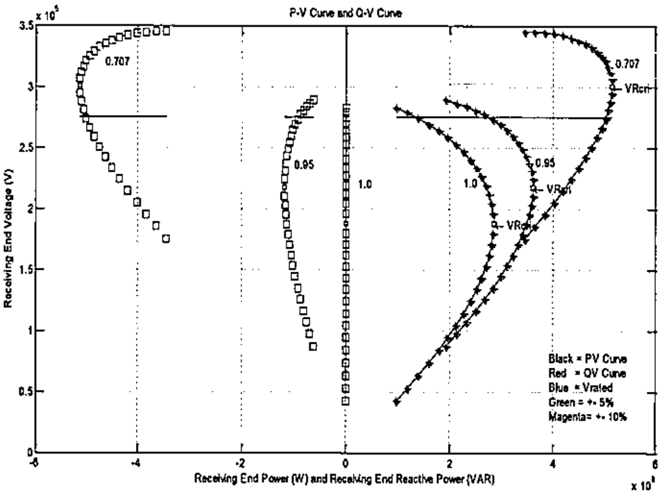

Fig. 15. PV and QV Curves for Medium-length Transmission Line at Very Bad (0.707), Unity (1.01) and Very Good (0.95) Leading Power Factor

Table V shows the data at the critical point of P-V and Q-V curve for various leading and unity power factor.

Table. 5. Results of medium-length transmission line at leading power factors.

Power Factor	V_{cri} (kV)	P_{Rmax} (MW)	Q_{Rmax} (MVAR)	I_R (A)	Vreg (%)	Vgap (%)
0.707	300.3	515	-515.5	1531	9.2	-9.2
0.8	267.5	462.8	-347.5	1215	7.7	2.7
0.85	250.9	432.8	-268.3	1069	8.8	8.8
0.9	234.5	400	-194	933.9	10.9	14.7
0.95	217.2	362.4	-119.2	800.9	13.9	21

6. CONCLUSION

Voltage instability analysis plays significant role in monitoring the magnitude of feeder voltage in order to avoid the system from operating near the critical point. The values of critical voltage for lagging condition are smaller than leading condition. As a result, lagging condition provides wider range of voltage gap compared to the leading condition; besides, it provides wider operating condition to ensure voltage stability. The values of voltage regulation for leading condition are smaller due to voltage rises at the receiving end of the feeder caused by capacitive current injection. Leading condition produces higher line currents that may exceed the rated current line carrying capability or MVA rating of the line which is undesirable. The combination of P-V and Q-V curves for voltage instability analysis incorporated in GUI based MATLAB environment has resulted in a user friendly approach tool for analysing voltage stability of radial power system feeders. The GUI is designed to display important data such as critical voltage, voltage gap, allowable operating point, voltage regulation and real and reactive powers and line currents. This GUI software package is an ideal tool that can be used for teaching and learning purposes for engineering students and training practicing engineers.

REFERENCES

[1] R. Omar, M. Rasheed, A. Al-janad, and M. Sulaiman, "Australian Journal of Basic and Applied Sciences Harmonic Reduction for Diode Clamped and Cascaded H-Bright , Five to Nine Levels of Multilevel Inverters Application," vol. 8, no. March, pp. 211–227, 2014.
[2] R. Omar, M. Rasheed, A. Al-janad, M. Sulaiman, and Z. Ibrahim, "HARMONIC REDUCTION COMPARISON IN MULTILEVEL INVERTERS FOR INDUSTRIAL APPLICATION," vol. 63, no. 3, pp. 570–578, 2014.
[3] R. Omar, M. Rasheed, M. Sulaiman, and A. Al-janad, "A Study of a Three Phase Diode Clamped Multilevel Inverter Performance For Harmonics Reduction," MAGNT Res. Rep. (ISSN. 1444-8939), vol. 2, no. 4, pp. 62–71.
[4] *ns*. IEEE Power Engineering Review, September 2000, 0272-1724/00, pp.46-47.

[5] Dorf, 2007. *Electric Power Engineering Handbook*: *Power system Stability and Control* (Grigsby, 2nd ed.), Boca Raton: CRC Press.

[6] Glover, Sarma, Overbye and Carson, 2007. *Power System Analysis and Design*, 4th ed., Ontario: Thomson Engineering.

[7] Gonen, 2008. *Electric Power Distribution System Engineering*, 2nd ed., New York: CRC Press.
[8] Khan, A.A., 2007. *A Simple Method for Tracing PV Curve of a Radial Transmission Line*. World Academy of Science, Engineering and Technology, 37 2008, pp.331-334.

[9] Kundur, P., Paserba, J., Ajjarapu, V., Andersson, G., Bose, A., Canizares, C., Hatziargyriou, N., Hill, D., Stankovic, A., Taylor, C., Cutsem, T.V. and Vittal, V., 2004. *Definition and Classification of Power System Stability*. IEEE/CIGRE Joint Task Force on Stability Terms and Condition, IEEE Transaction on Power System, Vol. 19(2), pp.1387-1401.
[10] Ray, S., 2007. *Electrical Power Systems: Concepts, Theory and Practice,* New Delhi: Prentice Hall of India Pvt. Ltd.
[11] Saadat, 1999. *Power System Analysis, International* ed., Singapore: McGraw-Hill.

[12] Tenaga Nasianal Berhad. (2014). *TNB Electricity System* [online] Available: http://www.tnb.com.my/business/for-housing-developers-electrical-contractors/tnb-electricity-system.html
[13] Vargas, L.M., Jatskevich, J., and Marti, J.R., 2009. *Induction Motor Loads and voltage Stability Assessment Using PV Curves*. IEEE Conference Publication, 978-1-4244-4241-6/09, pp.1-4.
[14] Crappe, 2008. *Electric Power System,* Hoboken: John Wiley & Sons.
[15] Gilat, A., 2007. *MATLAB: An Introduction with Applications, 3rd ed.,* Ohio: John Wiley & Sons.
[16] Palm III, W.J., 2007. *A Concise Introduction to MATLAB,* New York: McGraw-Hill.
[17] Moore, H., 2009. *MATLAB for Engineers, 2nd ed..,* New Jersey: Prentice-Hall.
[18] Palm III, W.J., 2005. *Introduction to MATLAB 7 for Engineers,* New York: McGraw-hill.
[19] R. Omar, M. Rasheed, M. Sulaiman, and A. Al- janad, "A Study of a Three Phase Diode Clamped Multilevel Inverter Performance For Harmonics Reduction," *MAGNT Res. Rep. (ISSN. 1444-8939),* vol. 2, no. 4, pp. 62–71.

http://www.tnb.com.my/business/for-housing-developers-electrical-contractors/tnb-electricity-system.