USE OF ENERGY FUNCTION TO ASSESS VOLTAGE STABILITY OF A FOUR-BUS POWER SYSTEM WITH A SVC

[1]AHMET CIFCI, [2]YILMAZ UYAROGLU

[1]Mehmet Akif Ersoy University, [2]Sakarya University
E-mail: [1]acifci@mehmetakif.edu.tr, [2]uyaroglu@sakarya.edu.tr

Abstract- Electric power systems are more heavily loaded than ever before. That makes power systems operate in critical position at the boundary of voltage stability region. This paper discusses the effects of a static VAr compensator (SVC) to improve voltage stability of a four-bus power system. Energy function analysis by using the variable gradient method is employed. The numerical simulations demonstrate that the use of SVC improves voltage stability.

Index Terms- Energy function, four-bus power system, static VAr compensator, voltage stability.

I. INTRODUCTION

Electric power systems are becoming overly stressed due to growing demand and are threatened by the probability of voltage instability and voltage collapse. Voltage stability has been given much attention after a number of major incidents throughout the world [1]-[3]. Voltage stability problems usually occur on power systems which are heavily loaded. The recent advances in power electronics introduce the use of flexible alternating current transmission systems (FACTS) devices in power systems. In 1988, Hingorani [4] introduced the concept of FACTS. Edris et al. [6] proposed terms and definitions for different FACTS devices. FACTS is defined by the IEEE as "a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability" [5]. The use of FACTS devices improves control of the reactive power flow thereby enhancing voltage stability. Among the different FACTS devices, static VAr compensator (SVC) has been effectually used to improve the voltage profile at the buses [6]. SVC is a shunt-connected and a first generation FACTS device that uses its reactive capability to alter the bus voltage. SVC is used in power systems primarily for voltage control or for improving system stability. The effectiveness of SVC depends on its optimal location. Ideally, SVC should be placed at the electrical centre of the system or midpoint of a transmission line [7]. Perez et al. [8] examined the co-ordinated application of FACTS devices to improve small-disturbance voltage stability in power systems. The potential for voltage stability improvement of FACTS devices is shown. In [9], a comprehensive and comparative analysis of FACTS devices for improving system static performance is presented. Subramanian et al. [10] analysed the impact of SVC on bifurcations, chaos and voltage collapse in power systems. This paper focuses on voltage stability analysis of a four-bus power system with and without SVC by applying Lyapunov (energy) function based on the variable gradient method.

The rest of the paper is organized as follows. Section 2 provides outlines of the variable gradient method for constructing a suitable energy function. The design principles of SVC are explained in section 3. Section 4 presents the description of power system models used in this study. The simulation results and energy function analysis are presented in section 5. The last section summarizes the results and draws the conclusion.

II. THE VARIABLE GRADIENT METHOD

Energy function is a powerful tool of assessing stability of a power system. It is based on the Lyapunov's second method (also called Lyapunov's direct method). Lyapunov's second method allows stability of a system to be verified without solving the differential equation explicitly. Unfortunately, Lyapunov function method gives no indication of how to find a Lyapunov function. Some approaches like the variable gradient method to finding a Lyapunov function are suitable. This section continues by reviewing the variable gradient method [11]-[13].

Consider the nonlinear system

$$\dot{x} = f(x,t) \qquad (1)$$

Denote a test Lyapunov function by using V and its time derivative $\dot{V}$. In (1), V is x's open function but not t's.

$$\dot{V} = \frac{\partial V}{\partial x_1}\frac{dx_1}{dt} + \frac{\partial V}{\partial x_2}\frac{dx_2}{dt} + \ldots + \frac{\partial V}{\partial x_n}\frac{dx_n}{dt} \qquad (2)$$

Denoted in terms of the gradient, (2) can be written as:

$$\dot{V} = (\nabla V)^* \dot{x} \qquad (3)$$

where $(\nabla V)^*$ is the transpose of ∇V. V is obtained as a line integral of ∇V, as:

$$V = \int_0^x (\nabla V)^* dx \qquad (4)$$

The integral's upper limit here does not point that V is a vector quantity, but integral is preferred to line integral of a random point $(x_1,x_2,\ldots,x_n)$ at the phase-space. This integral can be made independent of integration method.

A gradient system of the form can be written as follows [14]:

$$\dot{x} = -A\nabla V(x,x_0) \qquad (5)$$

where V: $\Re^n x \Re^n \to \Re$ is a continuously differentiable function, $A \in \Re^{nxn}$, det(A)≠0 and $V(x,x_0)=0$ at $x=x_0$. If the Hessian of $V(x,x_0)$ is completely positive definite at x_0, the equilibrium point is asymptotically stable at x_0. Lyapunov (energy) function is given as:

$$V(x) = \int_{x_0}^{x} \left[f(\xi)\right]^T d\xi \qquad (6)$$

III. STATIC VAR COMPENSATOR

As part of the FACTS device family, SVC provides voltage regulation and system stabilization by compensating reactive power in the grid. In general, SVC consists of three main components and their combination: Thyristor-controlled reactor (TCR), thyristor-switched reactor (TSR) and thyristor-switched capacitor (TSC). Also, a SVC system may include mechanically-switched capacitor (MSC), mechanically-switched reactor (MSR), fixed capacitor (FC), fixed reactor (FR) and harmonic filters.

SVC is modelled as a first order time delay model as shown in Fig. 1.

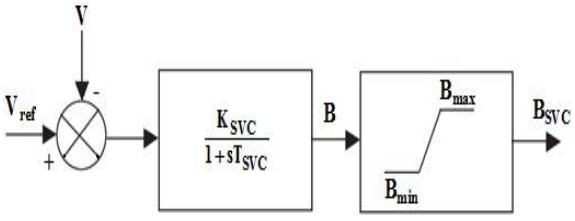


Figure 1. Block diagram of SVC

The dynamics of SVC are described by the following equations [15]:

$$\left.\begin{aligned} \dot{B} &= \frac{1}{T_{SVC}}(K_{SVC}(V_{ref} - V) - B) \\ B_{min} &\le B \le B_{max} \end{aligned}\right\} \qquad (7)$$

where B is the susceptance of SVC, K_{SVC} is SVC gain, T_{SVC} is the time constant of SVC and V_{ref} is the reference voltage. SVC hard limiters are modelled by using tanh function. For a susceptance B with limits $\pm B_{LIMIT}$, the output of the limiter is given by

$$B_{SVC} = B_{LIMIT} \tanh\left(\frac{B}{B_{LIMIT}}\right) \qquad (8)$$

Furthermore, an additional reactive power Q_{SVC} that is added to the load reactive power is given as

$$Q_{SVC} = BV^2 \qquad (9)$$

IV. POWER SYSTEM MODEL

The descriptions of the four-bus power system with and without SVC used in this study are as follows.

A. The Four-Bus Power System

A four-bus power system shown in Fig. 2 is considered. Two load buses 3 and 4 are fed by two generators 1 and 2. One-numbered-bus has been selected as a reference bus for the analyses. The network, load and generator parameters are presented in the Appendix.

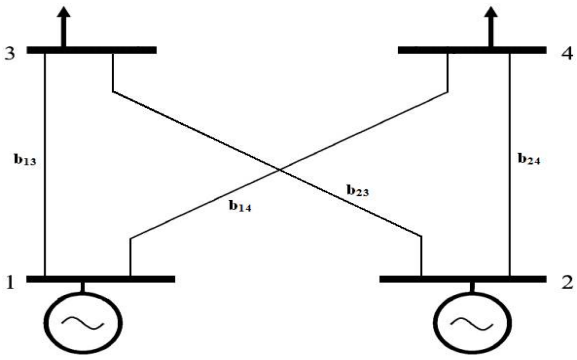


Figure 2. Four-bus power system

The load flow equations for four-bus power system can be written as follows:

$$\tilde{f}_2(\delta_2,V_2) = V_2V_3b_{23}\sin(\delta_2-\delta_3) + V_2V_4b_{24}\sin(\delta_2-\delta_4) \qquad (10)$$

$$\tilde{f}_3(\delta_3,V_3) = V_1V_3b_{13}\sin(\delta_1-\delta_3) + V_2V_3b_{23}\sin(\delta_3-\delta_2) \qquad (11)$$

$$\tilde{f}_4(\delta_4,V_4) = V_1V_4b_{14}\sin(\delta_1-\delta_4) + V_2V_4b_{24}\sin(\delta_4-\delta_2) \qquad (12)$$

$$\tilde{g}_2(\delta_2,V_2) = -V_2V_3b_{23}\cos(\delta_2-\delta_3) - V_2V_4b_{24}\cos(\delta_2-\delta_4)\ldots$$
$$-V_2^2(b_{23}+b_{24}) \qquad (13)$$

$$\tilde{g}_3(\delta_3,V_3) = -V_2V_3b_{23}\cos(\delta_2-\delta_3) - V_1V_3b_{13}\cos(\delta_3-\delta_1)\ldots$$
$$-V_3^2(b_{23}+b_{13}) \qquad (14)$$

$$\tilde{g}_4(\delta_4,V_4) = -V_1V_4b_{14}\cos(\delta_4-\delta_1) - V_2V_4b_{24}\cos(\delta_4-\delta_1)\ldots$$
$$-V_4^2(b_{14}+b_{24}) \qquad (15)$$

$$f_i(\delta_i,V_i) = \tilde{f}_i(\delta_i,V_i) + P_i^0 \qquad (16)$$

$$g_i(\delta_i,V_i) = \tilde{g}_i(\delta_i,V_i) + Q_{D,i}(V_i) \qquad (17)$$

The load flow equations for four-bus power system above can be written again under the condition that

generator mechanical power is equivalent to active load requirement (P_M=P_L).

$$\dot{\delta}_3 = -D_3^{-1}\left\{V_1V_3b_{13}\sin(\delta_1-\delta_3)+V_2V_3b_{23}\sin(\delta_3-\delta_2)+P_3^0\right\} \quad (18)$$

$$\dot{\delta}_4 = -D_4^{-1}\left\{V_1V_4b_{14}\sin(\delta_1-\delta_4)+V_2V_4b_{24}\sin(\delta_4-\delta_2)+P_4^0\right\} \quad (19)$$

$$\dot{V}_3 = -\frac{1}{\dot{\varepsilon}}V_3^{-1}\{-V_2V_3b_{23}\cos(\delta_2-\delta_3)+V_3V_1b_{13}\cos(\delta_3-\delta_1)\ldots$$
$$-V_3^2(b_{23}+b_{13})+Q_{D,3}(V_3)\} \quad (20)$$

$$\dot{V}_4 = -\frac{1}{\dot{\varepsilon}}V_4^{-1}\{-V_1V_4b_{14}\cos(\delta_4-\delta_1)+V_4V_2b_{24}\cos(\delta_4-\delta_1)\ldots$$
$$-V_4^2(b_{14}+b_{24})+Q_{D,4}(V_4)\} \quad (21)$$

$$\dot{\omega}_1 = -M_1^{-1}\left\{-P_1^0\right\} \quad (22)$$

$$\dot{\omega}_2 = -M_2^{-1}\left\{V_2V_3b_{23}\cos(\delta_2-\delta_3)+V_2V_4b_{24}\sin(\delta_2-\delta_4)-P_2^0\right\} \quad (23)$$

B. The Four-Bus Power System with SVC

Consider the four-bus power system with SVC, as depicted in Fig. 3. SVC is connected to the three-numbered-load bus in order to examine voltage stability of the system when load is stable in four-numbered-bus.

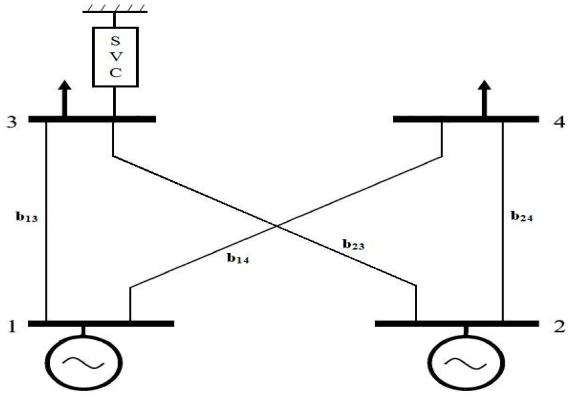


Figure 3. Four-bus power system with SVC

The load flow equations for four-bus power system with SVC can be written under the condition that generator mechanical power is equivalent to active load requirement (P_M=P_L).

$$\dot{\delta}_3 = -D_3^{-1}\left\{V_1V_3b_{13}\sin(\delta_1-\delta_3)+V_2V_3b_{23}\sin(\delta_3-\delta_2)+P_3^0+Q_{SVC}\right\} \quad (24)$$

$$\dot{\delta}_4 = -D_4^{-1}\left\{V_1V_4b_{14}\sin(\delta_1-\delta_4)+V_2V_4b_{24}\sin(\delta_4-\delta_2)+P_4^0\right\} \quad (25)$$

$$\dot{V}_3 = -\frac{1}{\dot{\varepsilon}}V_3^{-1}\{-V_2V_3b_{23}\cos(\delta_2-\delta_3)+V_3V_1b_{13}\cos(\delta_3-\delta_1)\ldots$$
$$-V_3^2(b_{23}+b_{13})+Q_{D,3}(V_3)-Q_{SVC}\} \quad (26)$$

$$\dot{V}_4 = -\frac{1}{\dot{\varepsilon}}V_4^{-1}\{-V_1V_4b_{14}\cos(\delta_4-\delta_1)+V_4V_2b_{24}\cos(\delta_4-\delta_1)\ldots$$
$$-V_4^2(b_{14}+b_{24})+Q_{D,4}(V_4)\} \quad (27)$$

$$\dot{\omega}_1 = -M_1^{-1}\left\{-P_1^0\right\} \quad (28)$$

$$\dot{\omega}_2 = -M_2^{-1}\left\{V_2V_3b_{23}\cos(\delta_2-\delta_3)+V_2V_4b_{24}\sin(\delta_2-\delta_4)-P_2^0\right\} \quad (29)$$

V. ENERGY FUNCTION ANALYSIS

Energy function analysis proposes a different perspective of voltage stability. Additional studies of energy function and construction of energy function can be found in [16-18], and the references cited therein.

If (18), (19), (20), (21), (22) and (23) or (24), (25), (26), (27), (28) and (29) are rewritten with respect to (10), (11), (12), (13), (14) and (15), the following equations are obtained.

$$\dot{\delta}_3 = -D_3^{-1}\left\{\tilde{f}_3(\delta_3,V_3)+P_3^0\right\} \quad (30)$$

$$\dot{\delta}_4 = -D_4^{-1}\left\{\tilde{f}_4(\delta_4,V_4)+P_4^0\right\} \quad (31)$$

$$\dot{V}_3 = -\frac{1}{\dot{\varepsilon}}V_3^{-1}\left\{\tilde{g}_3(\delta_3,V_3)+Q_{D,3}(V_3)\right\} \quad (32)$$

$$\dot{V}_4 = -\frac{1}{\dot{\varepsilon}}V_4^{-1}\left\{\tilde{g}_4(\delta_4,V_4)+Q_{D,4}(V_4)\right\} \quad (33)$$

$$\dot{\omega}_1 = -M_1^{-1}\left\{-\tilde{f}_1(1,0)-P_1^0\right\} \quad (34)$$

$$\dot{\omega}_2 = -M_2^{-1}\left\{-\tilde{f}_2(\delta_2,V_2)-P_2^0\right\} \quad (35)$$

For analysis of the four-bus power system with SVC, (30) and (32) can be written as:

$$\dot{\delta}_3 = -D_3^{-1}\left\{\tilde{f}_3(\delta_3,V_3)+P_3^0+Q_{SVC}\right\} \quad (36)$$

$$\dot{V}_3 = -\frac{1}{\dot{\varepsilon}}V_3^{-1}\left\{\tilde{g}_3(\delta_3,V_3)+Q_{D,3}(V_3)-Q_{SVC}\right\} \quad (37)$$

The derivation of Lyapunov function for the four-bus power system with and without SVC (30), (31), (32), (33), (34), (35), (36) and (37) can be determined as:

$$\begin{bmatrix}\dot{\delta}_3\\ \dot{\delta}_4\\ \dot{V}_3\\ \dot{V}_4\\ \dot{\omega}_1\\ \dot{\omega}_2\end{bmatrix} = \begin{bmatrix}-D_3^{-1} & 0 & 0 & 0 & 0 & 0\\ 0 & -D_4^{-1} & 0 & 0 & 0 & 0\\ 0 & 0 & -\frac{1}{\dot{\varepsilon}}V_3^{-1} & 0 & 0 & 0\\ 0 & 0 & 0 & -\frac{1}{\dot{\varepsilon}}V_4^{-1} & 0 & 0\\ 0 & 0 & 0 & 0 & -M_1^{-1} & 0\\ 0 & 0 & 0 & 0 & 0 & -M_2^{-1}\end{bmatrix}\begin{bmatrix}f(\delta_3,V_3)\\ f(\delta_4,V_4)\\ g(\delta_3,V_3)\\ g(\delta_4,V_4)\\ f(\delta_1,V_1)\\ f(\delta_2,V_2)\end{bmatrix} \quad (38)$$

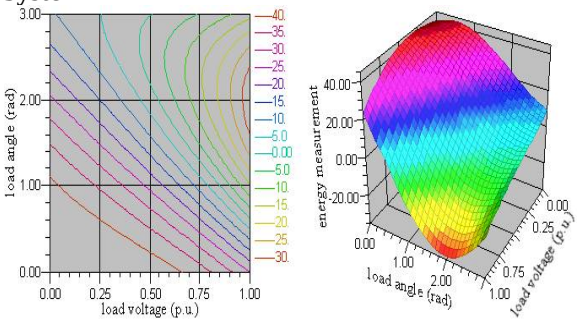
Equation (38) is an alternative definition for dynamics of the four-bus power system with and without SVC. For [δ_3^0, δ_4^0, V_3^0, V_4^0, ω_1^0, ω_2^0]'s equilibrium point, a candidate energy function, which is seen on the right of the equation (38), ((6x1) gradient matrix) is obtained and thus it can be used in (6). The candidate energy function can be written in (6) as:

$$V(\delta_3,\delta_4,V_3,V_4,\omega_3,\omega_4) = \int_{(\delta_3^0,\delta_4^0,V_3^0,V_4^0,\omega_3^0,\omega_4^0)}^{(\delta_3,\delta_4,V_3,V_4,\omega_3,\omega_4)} \begin{bmatrix}f(\delta_3,V_3)\\ f(\delta_4,V_4)\\ g(\delta_3,V_3)\\ g(\delta_4,V_4)\\ f(\delta_1,V_1)\\ f(\delta_2,V_2)\end{bmatrix}^T \begin{bmatrix}d\delta_3\\ d\delta_4\\ dV_3\\ dV_4\\ d\omega_1\\ d\omega_2\end{bmatrix} \quad (39)$$

Lyapunov function V can be thought of as generalized

energy function for studied power systems. If (10), (11), (12), (13), (14) and (15) are replaced on (39), energy function of the four-bus power system with and without SVC is obtained [19]. Initial condition of the [δ_3^*, δ_4^*, V_3^*, V_4^*, ω_1^*, ω_2^*] was at the values of [-0.022, 0.068, 0.976, 1.02, 0.0, 0.0], respectively.
The generator angle of two-numbered-bus will be changed from 0.8 to 1.6 in order to observe the four-bus power system with and without SVC's voltage stability. The numerical simulations of the four-bus power system with and without SVC are carried out by using Macsyma [20].

C. Simulation Results for the Four-Bus Power System



(a) (b)

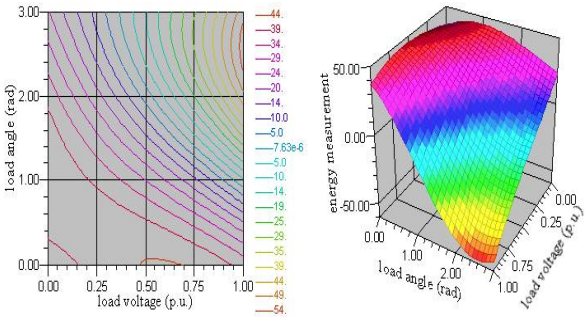
Figure 4. Stored energy for δ_2=0.8: (a) plot of the contours (b) 3D of the studied model

For δ_2=0.8 rad, Fig. 4 illustrates the voltage-angle trajectory of energy function mechanism. Fig. 4 and Tab. 1 demonstrate the energy density of the studied system. The energy density is in the range of 0≤ V≤0,6 and 0≤ δ≤1. The energy density varies between 19 and 44 energy units around these points.

Table 1. Energy measurement for δ_2=0.8

δ	Energy Measurement										
0	40	42	43	44	44	43	42	39	36	31	25
0,2	42	43	43	43	42	41	38	35	30	24	18
0,4	43	43	43	42	40	37	34	30	24	17	10
0,6	43	42	41	39	37	33	29	24	18	10	1
0,8	42	41	39	36	33	29	24	18	11	3	-7
1	41	39	36	33	29	24	19	12	5	-4	-14
1,2	39	36	33	29	24	19	13	6	-2	-10	-21
1,4	37	33	29	25	20	14	8	1	-7	-16	-26
1,6	33	29	25	21	16	10	4	-4	-11	-20	-30
1,8	30	26	21	17	11	6	0	-7	-15	-23	-32
V	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1

The numerical values of the energy function for different load angles and different load voltages for δ_2=0.8 rad are shown in Tab. 1.



(a) (b)

Figure 5. Stored energy for δ_2=1.6: (a) plot of the contours (b) 3D of the studied model

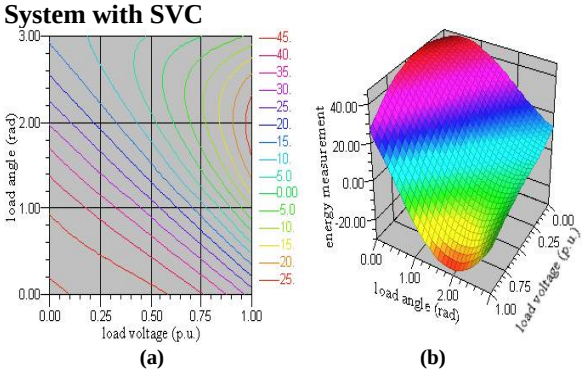
Fig. 5 exhibits the voltage-angle trajectory of energy function mechanism for δ_2=1.6 rad. The energy density of the studied system is indicated in Fig. 5 and Tab. 2. The energy density is in the range of 0≤ V≤0,8 and 0≤ δ≤1,6. Observe also that the energy density varies between -12 and 46 energy units around these points.

Table 2. Energy measurement for δ_2=1.6

δ	Energy Measurement										
0	36	39	41	43	44	45	46	45	44	41	38
0,2	39	41	42	44	44	44	44	42	40	37	32
0,4	41	42	43	43	43	42	41	38	35	30	25
0,6	43	43	43	42	41	39	36	33	28	23	16
0,8	44	43	42	40	38	35	31	27	21	14	7
1	44	43	40	38	34	30	26	20	13	5	-4
1,2	44	42	38	34	30	25	19	12	5	-4	-14
1,4	44	40	36	31	25	19	13	5	-4	-13	-24
1,6	42	38	32	27	21	14	6	-2	-12	-22	-33
1,8	41	35	29	23	16	8	0	-9	-19	-30	-41
V	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1

For δ_2=1.6 rad, Tab. 2 shows numerical values of the energy function for different load angles and different load voltages.

D. Simulation Results for the Four-Bus Power System with SVC



(a) (b)

Figure 6. Stored energy for δ_2=0.8: (a) plot of the contours (b) 3D of the studied model

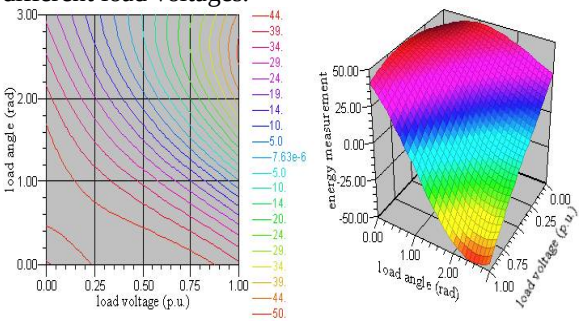
Fig. 6 shows the voltage-angle trajectory of energy function mechanism for δ_2=0.8 rad. Fig. 6 and Tab. 3 indicate the energy density of the studied system. The energy density is in the range of 0≤ V≤0,6 and 0≤ δ≤1. The energy density varies between 22 and 47 energy

units around these points.

Table 3. Energy measurement for δ_2=0.8

δ	Energy Measurement										
0	43	45	46	47	47	46	45	42	39	34	28
0,2	45	46	47	46	46	44	42	38	33	28	21
0,4	46	46	46	45	43	41	37	33	28	21	13
0,6	46	46	44	43	40	37	33	27	21	14	5
0,8	46	44	42	40	36	32	28	22	15	7	-3
1	45	42	39	36	32	28	22	16	9	0	-10
1,2	42	40	36	32	28	23	17	10	3	-6	-16
1,4	40	36	32	28	23	18	12	5	-3	-11	-21
1,6	37	33	29	24	19	14	8	1	-7	-15	-25
1,8	33	29	25	20	15	10	4	-3	-10	-18	-27
V	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1

For δ_2=0.8 rad, Tab. 3 demonstrates numerical values of the energy function for different load angles and different load voltages.



(a) **(b)**

Figure 7. Stored energy for δ_2=1.6: (a) plot of the contours (b) 3D of the studied model

Fig. 6 exhibits the voltage-angle trajectory of energy function mechanism for δ_2=0.8 rad. The energy density of the studied system is indicated in Fig. 6 and Table 3. The energy density is in the range of 0≤ V≤0,8 and 0≤ δ≤1,6. Observe also that the energy density varies between -7 and 49 energy units around these points.

Table 4. Energy measurement for δ_2=1.6

δ	Energy Measurement										
0	39	42	44	46	48	49	49	48	47	44	41
0,2	42	44	46	47	48	48	47	46	43	40	36
0,4	44	46	46	47	47	46	44	42	38	34	28
0,6	46	46	46	46	44	43	40	37	32	27	20
0,8	47	47	45	44	42	39	35	30	25	18	11
1	48	46	44	41	38	34	29	24	17	9	1
1,2	48	45	42	38	34	29	23	16	9	0	-9
1,4	47	43	39	34	29	23	17	9	1	-9	-19
1,6	46	41	36	30	24	18	10	2	-7	-17	-28
1,8	44	38	32	26	19	12	4	-5	-14	-25	-36
V	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1

The numerical values of the energy function for different load angles and different load voltages for δ_2=1.6 rad are indicated in Tab. 4.

It is observed that the system can work stable in the lower loads for δ_2=0.8 rad values of the generator angle. At the same time, in the large loads it is moving to instability. Hence, if the system works under large loads, generator angle must be chosen as δ_2=1.6 rad. It is also noticed that SVC is improve the level of energy density. When SVC is not considered, maximum energy level is 46 energy units (see Fig. 5 and Tab. 2). When the four-bus power system with SVC is considered, maximum energy level is increased to 49 energy units (see Fig. 7 and Tab. 4).

CONCLUSION

The application of the variable gradient method for voltage stability is studied in this paper. A four-bus power system is considered as an application example of the method proposed. The simulations show how system behavior changes by incorporating SVC. The results demonstrate the effectiveness of SVC. Future works will be focused on energy function analysis of power systems including other FACTS devices.

APPENDIX

The parameters considered for simulation are given below. All values are in per unit except for angles, which are in radian.

Parameters	Value	Parameters	Value
b_{13}	19.841	V_1	1
b_{14}	26.881	V_2	0.988
b_{23}	26.881	V_3	0.976
b_{24}	15.723	V_4	1.02
P_1	0.52	δ_1	0
P_2	1.7	δ_2	0.003
P_3	2	δ_3	-0.022
P_4	3.18	δ_4	0.068
Q_{D1}	0	Q_{D2}	0
Q_{D3}	1.239	Q_{D4}	1.239

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