ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 7, Issue 3, May 2018

Feedback Stabilization Control of Electrical Power Systems

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***Abstract*—A state feedback control law is proposed for electric power systems to delay and/or eliminate the so-called "voltage collapse" behavior due to the occurrence of the saddle-node bifurcation or Andronov-Hopf bifurcation. Based on a previous study (Liaw et al, 2005), in this paper a linear feedback stabilizing control law is designed at the Andronov-Hopf bifurcation point, which will then delay and/or eliminate the appearance of the bifurcation phenomena as well as voltage collapse in the power system. Numerical simulations demonstrate the success of the proposed design.**

***Index Terms*—power systems, voltage collapse, control.**

I. INTRODUCTION

The study of voltage collapse phenomena in real-world electric power systems has recently attracted lots of attention [1]-[5]. It is due to the power systems facing growing load demands but with little addition of the power generation and transmission facilities, which will lead the power systems to be operated near the stability limits. As the load demands become too heavy to offer, the magnitude of load voltage falls sharply to a very low level. Such a phenomena is the so-called "voltage collapse." It is known that the phenomenon of voltage collapse might be attributed to the occurrence of the saddle-node bifurcation [2] or Andronov-Hopf bifurcation [3]. In a previous study [5], we have obtained a bifurcation analysis of nonlinear dynamics for electric power system with tap changer. That study was based on a model of electric power system proposed by Dobson and Chiang [1] with one extra tap changer added parallel to the local nonlinear power load. The saddle-node bifurcation and Hopf bifurcations were both observed in [5] by treating the real power, reactive power and tap changer as system parameters, which lead to the appearance of static and dynamic voltage collapses, respectively. Those phenomena may generate the progressive decrease in voltage magnitude in electric power system. In the recent years, the Static Var Compensator (SVC) has been considered as a control actuator for improving system stability (e.g., [3]-[4]). For instance, a washout filter-aided feedback design was proposed in [3] to delay the occurrence of the system instability and/or voltage collapse. A sliding-mode based design was proposed to regulate the load voltage [4]. Instead of controlling the system behavior via the SVC, in this paper we consider a different approach by tuning the ratio of the tap changer to prevent and/or delay the appearance of voltage collapse.

The organization of the paper is as follows. First, we recall the model of the electric power systems from [2] and [5]. A design of control laws for an example system is proposed in Section III. Numerical results were obtained and given in Section IV to demonstrate the success of the proposed scheme. Finally, conclusion is also given in Section V to highlight the major contributions and possible applications.

II. ELECTRIC POWER SYSTEMS

In this section, we will first recall the mathematical model proposed by Dobson and Chiang ([1]-[2]) for electric power systems as given by

$$\dot{\delta}_m = \omega_m \tag{1}$$

$$M\dot{\omega}_m = P_m - d_m\omega_m + E_m{}^2 Y_m \sin\theta_m + E_m Y_m V \sin(\delta - \delta_m - \theta_m) \tag{2}$$

$$k_{qw}\dot{\delta} = -k_{qv^2}V^2 - k_{qv}V + Q(\delta_m, \delta, V) - Q_0 - Q_1 \tag{3}$$

$$Tk_{qw}k_{pv}\dot{V} = k_{p\omega}k_{qv^2}V^2 + (k_{p\omega}k_{qv} - k_{q\omega}k_{pv})V + k_{q\omega}(P(\delta_m, \delta, V) - P_0 - P_1) - k_{p\omega}(Q(\delta_m, \delta, V) - Q_0 - Q_1) \tag{4}$$

Where δ_m, ω_m, δ and V denote the generator phase angle, the generator phase angle velocity, the phase angle of the load voltage and the load voltage, respectively, and the nonlinear PQ load are given as

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
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$$P(\delta_m,\delta,V)=(Y_0{'}\sin\theta_0{'}+Y_m\sin\theta_m)V^2-E_mY_mV\sin(\delta-\delta_m+\theta_m)-E_0{'}Y_0{'}V\sin(\delta+\theta_0{'}) \quad (5)$$

$$Q(\delta_m,\delta,V)=-(Y_0{'}\cos\theta_0{'}+Y_m\cos\theta_m)V^2+E_mY_mV\cos(\delta-\delta_m+\theta_m)+E_0{'}Y_0{'}V\cos(\delta+\theta_0{'}) \quad (6)$$

with

$$E_0{'}=E_0[1+C^2Y_0^{-2}-2CY_0^{-1}\cos\theta_0]^{-\frac{1}{2}} \quad (7)$$

$$Y_0{'}=Y_0[1+C^2Y_0^{-2}-2CY_0^{-1}\cos\theta_0]^{\frac{1}{2}} \quad (8)$$

$$\theta_0{'}=\theta_0+\tan^{-1}\{\frac{CY_0^{-1}\sin\theta_0}{1-CY_0^{-1}\cos\theta_0}\} \quad (9)$$

Detailed definitions of each system parameter and derivations of the model equations above can be referred to [2]. By adopting the schematic diagram depicted in Fig. 1, a study of electric power systems with the tap changer was presented in [5]. It is clear from Fig. 1 that the tap changer is added in parallel with PQ-load. Based on the parameter values given in Table 1, a bifurcation diagram was obtained as shown in Fig. 2 for the electric power system with tap changer ratio n=1 and extra real load P_1=0. Note that, the symbols of HB, PD, CFB and SNB in Fig. 2 denote the Andronov-Hopf bifurcation, period-doubling bifurcation, cyclic-fold bifurcation and saddle-node bifurcation, respectively. The corresponding values of each bifurcation point are given in Table 2. In addition, the solid-line denotes the stable equilibrium point, while the dashed-line is unstable one. Nonlinear dynamical behaviors with different values of PQ-load were obtained as shown in Figs. 3 and 4. It is observed from Fig. 3 that the system might exhibit chaos-like behavior for P_1=0 and Q_1=11.281.

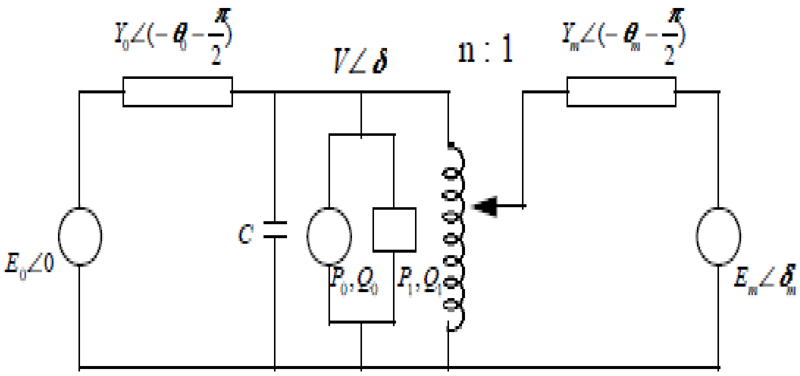

Fig. 1 Schematic diagram of electric power system with tap changer

Table 1 Parameter values for simulation

$K_{pw}=0.4$ p.u.	$K_{pv}=0.3$ p.u.	$K_{qw}=-0.03$ p.u.
$K_{qv}=-2.8$ p.u.	$K_{qv2}=2.1$ p.u.	$T=8.5$ p.u.
$P_0=0.6$ p.u.	$Q_0=1.3$ p.u.	$M=0.3$
$Y_0=20$ p.u.	$\theta_0=-5$ deg.	$E_0=1.0$ p.u.
$C=12$ p.u.	$Y_m=5.0$ p.u.	$\theta_m=-5$ deg.
$E_m=1.0$ p.u.	$P_m=1.0$ p.u.	$d_m=0.05$ p.u.

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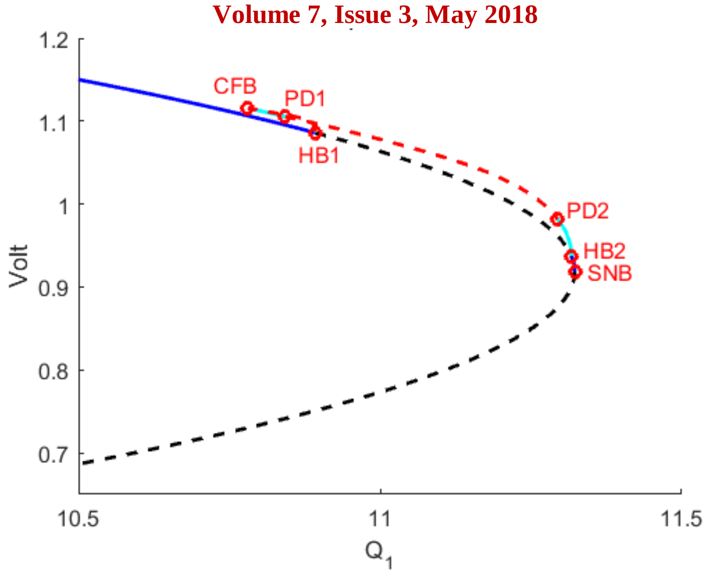

Fig. 2 Bifurcation diagram of open-loop system

Table 2 Bifurcation points

	Q_1(p.u.)	δ_m(rad)	ω_m(p.u.)	δ(rad)	V(p.u.)
HB1	10.8922382	0.3155862	0.0	0.1242236	1.0859983
HB2	11.3172630	0.3480599	0.0	0.1400899	0.9371622
SNB	11.3226426	0.3525217	0.0	0.1420761	0.9184196
CFB	10.7807797	0.7617265	1.5461432	0.2643184	1.1155829
PD1	10.8424025	0.7473045	1.4709736	0.2703874	1.1056323
PD2	11.2944940	0.4155393	0.2188148	0.1662050	0.9817292

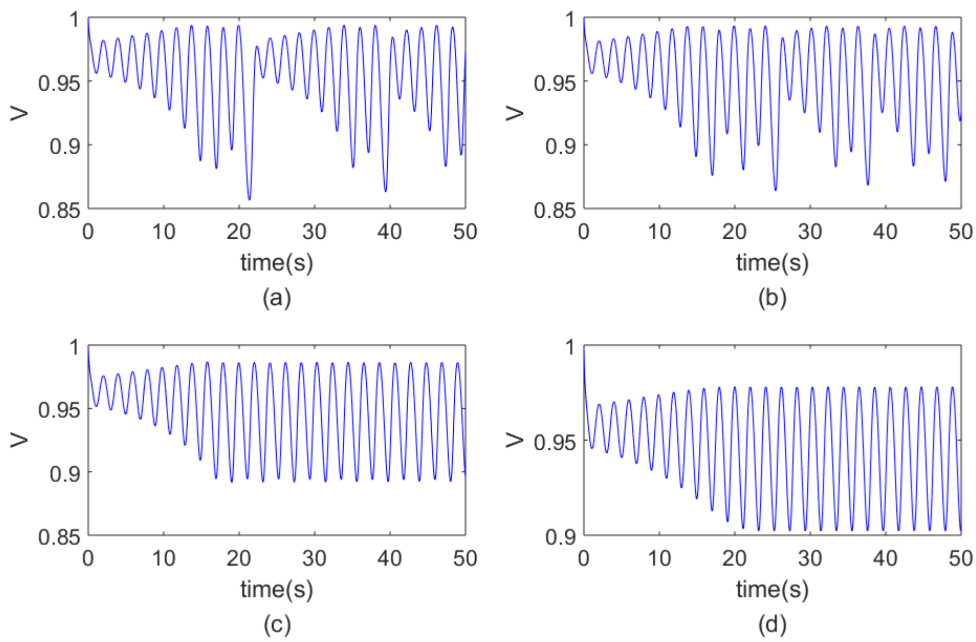

Fig. 3 Timing response of open-loop system at $Q_1 = 11.281$ **: (a)** $P_1 = 0$ **; (b)** $P_1 = 0.01$ **; (c)** $P_1 = 0.1$ **; and (d)** $P_1 = 0.2$

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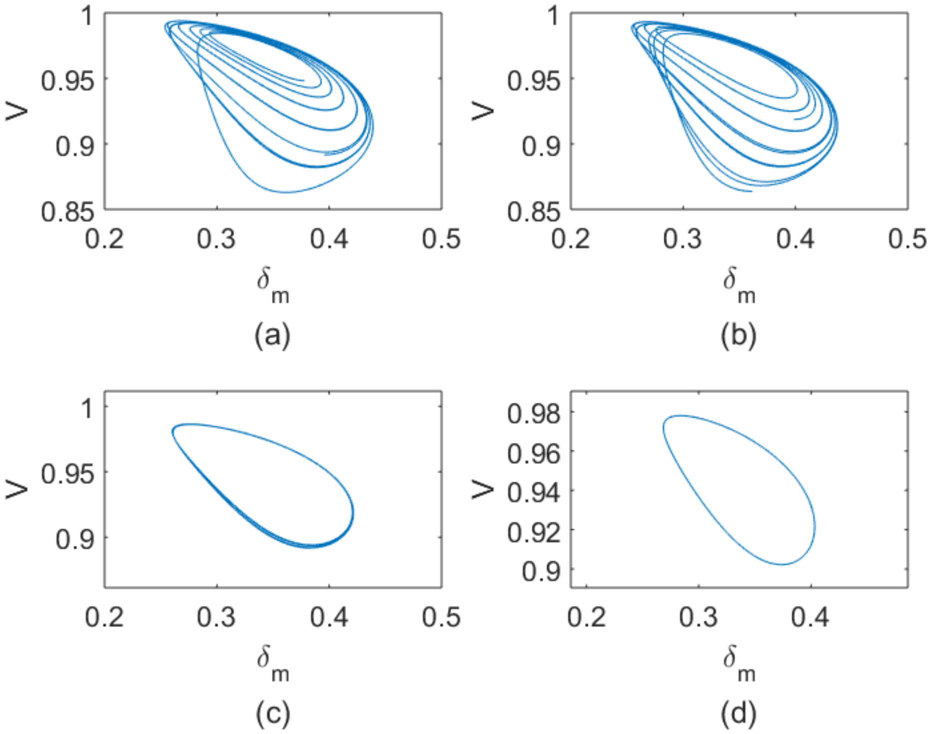

Fig. 4 Phase-diagram of open-loop system at $Q_1 = 11.281$ **: (a)** $P_1 = 0$ **; (b)** $P_1 = 0.01$ **; (c)** $P_1 = 0.1$ **; and (d)** $P_1 = 0.2$

III. DESIGN OF CONTROL LAWS

As discussed in [5], a major problem of electric power system is that the line voltage in PQ-load may jump sharply from the rated voltage to a deeply low voltage as PQ-load varies. In addition, It was concluded [5] that the voltage collapse would be mainly attributed to the occurrence of subcritical Hopf bifurcation or saddle-node bifurcation. As given in [5], Hopf bifurcation occurs first as the PQ-load changes. Thus, the control of Hopf bifurcation becomes a major issue in the design of prevention of voltage collapse. In this study, we will focus on the design of control laws to eliminate and/or delay the occurrence of Hopf bifurcation as well as voltage collapse phenomena. Here, for practical implementation, we only consider the tap changer ratio as the solely control signal for the electric power systems.

In the following discussion, we assume that the values of real power demand, reactive power demand and tap changer ratio can be varied. Let the control input u be defined as the difference of tap changer ratio, i.e., $u=1/n-1/n_0$, where n_0 denotes the nominal value of the tap changer. We then have the modified model of electric power systems as given below:

$$\dot{\delta}_m = \omega_m \tag{10}$$

$$M\dot{\omega}_m = P_m - d_m\omega_m + E_m{}^2 Y_m \sin\theta_m + E_m Y_m V(n_0{}'+u)\sin(\delta-\delta_m-\theta_m) \tag{11}$$

$$k_{qw}\dot{\delta} = -k_{qv^2}V^2 - k_{qv}V + Q(\delta_m,\delta,V) - Q_0 - Q_1 \tag{12}$$

$$\begin{aligned} Tk_{qw}k_{pv}\dot{V} &= k_{p\omega}k_{qv^2}V^2 + (k_{p\omega}k_{qv} - k_{q\omega}k_{pv})V \\ &\quad + k_{q\omega}(P(\delta_m,\delta,V) - P_0 - P_1) - k_{p\omega}(Q(\delta_m,\delta,V) - Q_0 - Q_1) \end{aligned} \tag{13}$$

with

$$\begin{aligned} P(\delta_m,\delta,V) &= (Y_0{}'\sin\theta_0{}' + Y_m(n_0{}'+u)^2\sin\theta_m)V^2 - E_m Y_m V(n_0{}'+u)\sin(\delta-\delta_m+\theta_m) \\ &\quad - E_0{}'Y_0{}'V\sin(\delta+\theta_0{}') \end{aligned} \tag{14}$$

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ISO 9001:2008 Certified
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$$Q(\delta_m,\delta,V)=-[Y_0'\cos\theta_0'+Y_m(n_0'+u)^2\cos\theta_m]V^2 + E_mY_mV(n_0'+u)\cos(\delta-\delta_m+\theta_m)+E_0'Y_0'V\cos(\delta+\theta_0') \quad (15)\&(16)$$

where $n_0'=1/n_0$.

Consider system (10)-(13) with control input $u=k_1\hat{x}_1+k_2\hat{x}_2+k_3\hat{x}_3+k_4\hat{x}_4$, where $\hat{x}_1=x_i-x_{i0}$ for i =1, ⋯, 4 and $X_0=[x_{10},x_{20},x_{30},x_{40}]^T$ denotes the Hopf bifurcation point HB1 as in Table 2. For simplicity and without loss of generality, in this study we take the parameter values as given in Table 1 for facilitating the design of control law. Taking the linearization of (10)-(13) at X_0, we then have

$$\dot{\hat{x}}=A_0\hat{x}+Bu \quad (17)$$

Where

$$A_0=\begin{bmatrix}0&1&0&0\\a_{21}&a_{22}&a_{23}&a_{24}\\a_{31}&0&a_{33}&a_{34}\\a_{41}&0&a_{43}&a_{44}\end{bmatrix} \text{ and } B=\begin{bmatrix}0\\b_2\\b_3\\b_4\end{bmatrix},$$

with

$$a_{21}=-16.6667n_0'x_{40}\cos(0.08727-x_{10}+x_{30})$$
$$a_{22}=-0.166667$$
$$a_{23}=16.6667n_0'x_{40}\cos(0.08727-x_{10}+x_{30})$$
$$a_{24}=16.6667n_0'\sin(0.08727-x_{10}+x_{30})$$
$$a_{31}=166.667n_0'x_{40}\sin(0.08727+x_{10}-x_{30})$$
$$a_{33}=-33.3333(20x_{40}\sin(0.216533-x_{30})+5n_0'x_{40}\sin(0.08727+x_{10}-x_{30}))$$
$$a_{34}=-33.3333(2.8-2(10.02389+4.98097n_0'^2)x_{40}+20\cos(0.216533-x_{30}) +5n_0'\cos(0.08727+x_{10}-x_{30}))$$
$$a_{41}=-13.0719(-0.15n_0'x_{40}\cos(0.08727+x_{10}-x_{30})+2n_0'x_{40}\sin(0.08727+x_{10}-x_{30}))$$
$$a_{43}=-13.0719(0.6x_{40}\cos(0.216533-x_{30})+0.15n_0'x_{40}\cos(0.08727+x_{10}-x_{30}) -8x_{40}\sin(0.216533-x_{30})-2n_0'x_{40}\sin(0.08727+x_{10}-x_{30}))$$
$$a_{44}=-13.0719[-1.111+8.1237x_{40}+4.01092n_0'^2x_{40}-8\cos(0.216533-x_{30}) -2n_0'\cos(0.08727+x_{10}-x_{30})-0.6\sin(0.216533-x_{30}) -0.15n_0'\sin(0.08727+x_{10}-x_{30})]$$
$$b_2=16.6667x_{40}\sin(0.08727-x_{10}+x_{30})$$
$$b_3=-33.3333(-9.96194n_0'x_{40}^2+5x_{40}\cos(0.08727+x_{10}-x_{30}))$$
$$b_4=-13.0719(-0.4(-9.96194n_0'x_{40}^2+5x_{40}\cos(0.08727+x_{10}-x_{30})) -0.03(0.87156n_0'x_{40}^2+5x_{40}\sin(0.08727+x_{10}-x_{30})))$$

The characteristic equation of the closed-loop system is then calculated as

$$\lambda^4+(143.883+187913k_2-217.612k_3+33.9529k_4)\lambda^3 +(1903.64+1.87913k_1-3706.189k_2-221.908k_3+2275.59k_4)\lambda^2 +(1991.59-3706.18k_1-3771.26k_2-3854.91k_3+978.724k_4)\lambda +26156.2-3771.26k_1-3380.59k_3+32470.2k_4=0. \quad (18)$$

By applying the Routh-Hurwitz stability criterion to (18), we then have the following results.

Lemma 1. The equilibrium point HB1 of system (10)-(13) is asymptotically stabilizable by the control input

ISSN: 2319-5967
ISO 9001:2008 Certified
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$u = k_1\hat{x}_1 + k_2\hat{x}_2 + k_3\hat{x}_3 + k_4\hat{x}_4$ if the following conditions hold :

(i) $143.883 + 1.87913k_2 - 217.612k_3 + 33.9529k_4 > 0$

(ii) $-1991.59 + 3706.18k_1 + 3771.26k_2 + 3854.91k_3 - 978.724k_4 + (143.883$
$+1.87913k_2 - 217.612k_3 + 33.9529k_4)(1903.64 + 1.87913k_1 - 3706.18k_2$
$-221.908k_3 + 2275.59k_4) > 0,$

(iii) $-(1991.59 - 3706.18k_1 - 3771.26k_2 - 3854.91k_3 + 978.724k_4)^2$
$+(143.883 + 1.87913k_2 - 217.612k_3 + 33.9529k_4)(1991.59 - 3706.18k_1$
$-3771.26k_2 - 3854.91k_3 + 978.724k_4)(1903.64 + 1.87913k_1 - 3706.18k_2$
$-221.908k_3 + 2275.59k_4) - (143.883 + 1.87913k_2 - 217.612k_3 + 33.9529k_4)^2$
$(26156.2 - 3771.26k_1 - 3380.59k_3 + 32470.2k_4) > 0,$ and

(iv) $26156.2 - 3771.26k_1 - 3380.59k_3 + 32470.2k_4 > 0.$

Next result follows readily from Lemma 1.

Corollary 1. The equilibrium point HB1 of system (10)-(13) is guaranteed to be asymptotically stable by the control law of $u = k_1\hat{x}_1 + k_2\hat{x}_2 + k_3\hat{x}_3 + k_4\hat{x}_4$ if one of the following four conditions hold:

(i) $-62.5434 < k_1 < 0$ and $k_2 = k_3 = k_4 = 0,$

(ii) $-76.027 < k_2 < 0$ and $k_1 = k_3 = k_4 = 0,$

(iii) $k_3 < 0$ and $k_1 = k_2 = k_4 = 0,$

(iv) $k_4 > 0$ and $k_1 = k_2 = k_3 = 0.$

IV. NUMERICAL SIMULATIONS

In this paper, we choose $n_0 = 1$ for numerical study. As claimed in Lemma 1 and Corollary 1 above, only system equilibria near the equilibrium point HB1 can be guaranteed to be asymptotically stable. In order to study the non-local stability range of system equilibria with respect to the variation of PQ-load, by using code AUTO [6] we have obtained numerical results as given in Fig. 5 on the existence of saddle-node bifurcation and Andronov-Hopf bifurcations with respect to the variation of the reactive load Q_1 . Here, we choose k_4 as the unique control gain. It is clear from Fig. 5 that the value of the reactive load Q_1 for Andronov-Hopf bifurcation point HB1 has been enlarged from 10.8922382 to around 11.70. In addition, the time responses of the load voltage V for both of the open-loop system and the controlled system with respect to different value of the reactive load Q_1 are also obtained as shown in Fig. 6, respectively. From those diagrams, we can conclude that the open-loop unstable system equilibria can be stabilized by the proposed control law as stated in Lemma 1. Next, we consider to study the effect of different control gains on the existence of saddle-node bifurcation and Andronov-Hopf bifurcations. Here, we choose k_2 as the only control gain. As shown in Fig. 7, the Andronov-Hopf bifurcations will be delayed for $k_2 = -0.01$ and eliminated for $k_2 = -0.02$. However, the voltage collapse caused by saddle-node bifurcation will be retained.

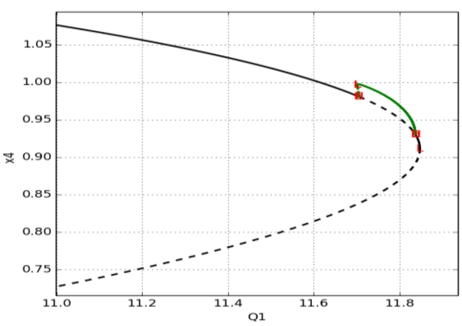

Fig. 5 Effect of $k_4 = 1$ on the bifurcation diagram

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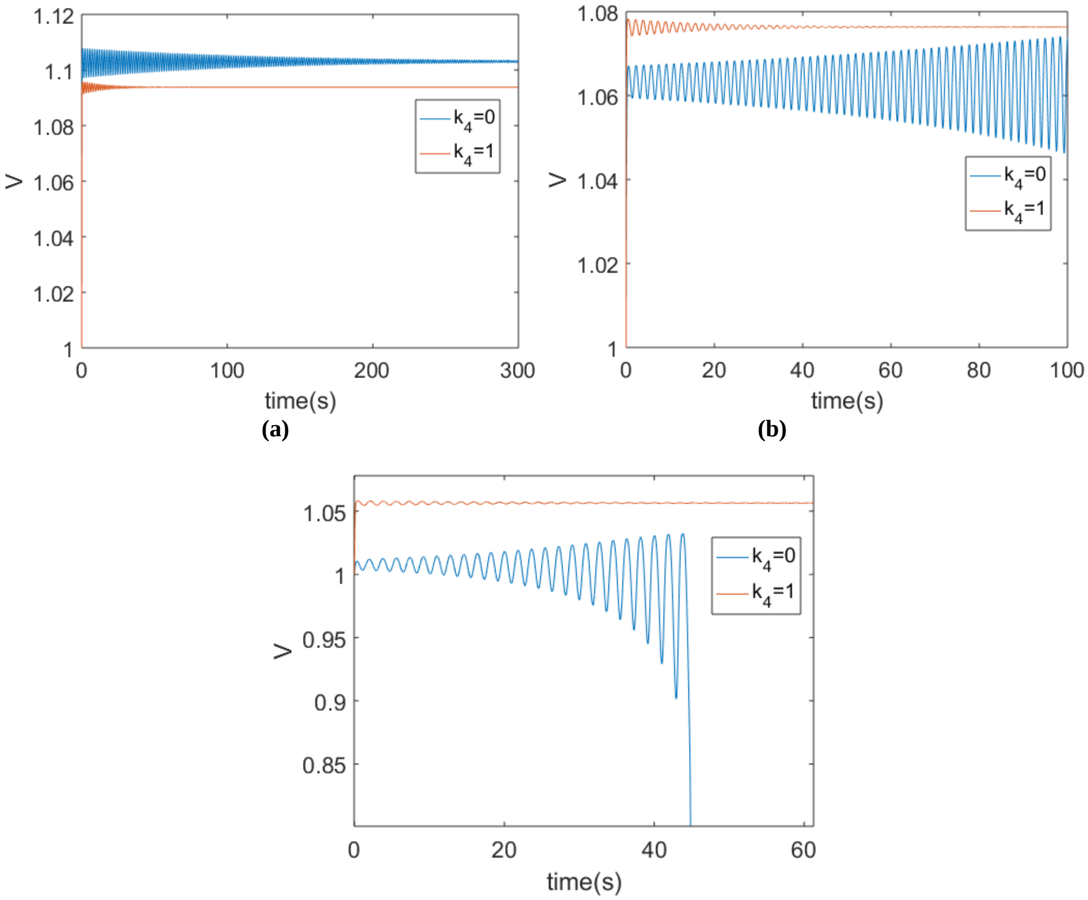
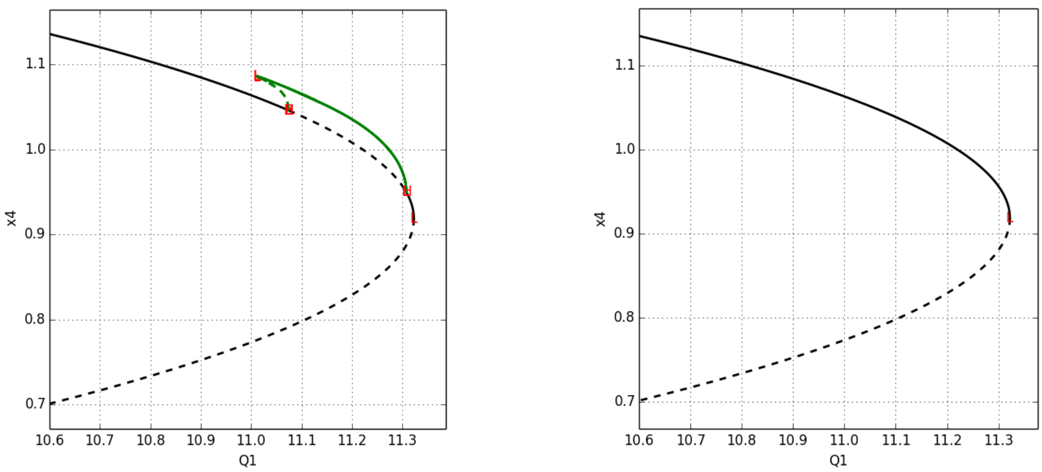


(a) (b)

(c)

Fig. 6 Effect of k_4 on the system stabilization: (a) $Q_1 = 10.8$; (b) $Q_1 = 11$; and (c) $Q_1 = 11.2$



(a) (b)

Fig. 7 Effect of k_2 on the bifurcation diagram: (a) $k_2 = -0.01$; and (b) $k_2 = -0.02$.

V. CONCLUSION

In this paper, we have further studied the stability results presented in [5] to design a stabilizing control law for delaying and/or eliminating the occurrence of voltage collapse behavior in electrical power systems via the tuning

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
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of the tap changer ratio. Numerical simulations were carried on to demonstrate the success of the proposed design. As observed from numerical simulations shown in Section IV, the voltage collapse behavior caused by Andronov-Hopf bifurcations can be delayed or eliminated via the proposed control laws. In addition, the effectiveness of the control efforts will be very different by using different control gains. For instance, a small variation of k_2 can make the system behavior very different, while a very large value of k_4 is needed to change system behavior. Those results might provide a guide in the practical application.

ACKNOWLEDGMENT

The authors would like to thank Jun-Wei Chen, Chin-Wen Tung and Hung-Tse Lee for helping the redo and check of numerical simulations as well as the editing of the final manuscript.

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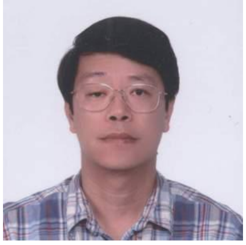

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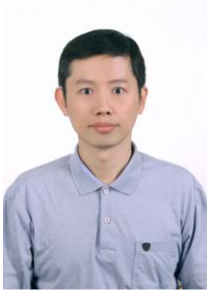

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