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Chaos control using self-feedback delay controller and electronic implementation in IFOC of 3-phase induction motor

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ABSTRACT The dynamical behaviors and chaos control in Indirect Field Oriented Control (IFOC) of 3-phase induction motor is investigated in the present paper. The IFOC of 3-phase induction motor exhibits steady state behavior, Hopf bifurcation and chaotic behavior through period-doubling. The chaotic behavior is strewed with periodic oscillation. To eliminate the chaotic oscillations in IFOC of 3-phase induction motor, two self-feedback delay controllers are designed: The first is the simple controller and the second controller is with sliding mode method. Numerical simulations are used to show the efficiency of the both controllers. Among the both controllers, the simple self-feedback delay controller gives the better results by comparison to sliding mode self-feedback delay controller. Finally, the physical feasibility of simple self-feedback delay controller applied to IFOC of 3-phase induction motor is validated through electronic circuit's implementation on OrCAD-PSpice software. The OrCAD-Pspice results are in agreement with the numerical results.

KEYWORDS
Chaotic attractor, Hopf birfucation, IFOC of 3-phase induction motor, Simple self-feedback delay controller, Circuit implementation.

INTRODUCTION

The success on nonlinear phenomena in many electronic systems stimulated research in other system especially the electrical machine. Many works have been done in Research on nonlinear phenomena like bifurcation and chaotic phenomena in electrical machine so, in 1989 by Kuroe et al. Kuroe and Hayashi (1989) applying the Poincaré map approach to analyzed the period doubling bifurcation in a three-phase inverter-fed induction drive system employing V/F control. In 1994, Nagy Nagy (1994) studied the bifurcation and chaotic phenomena in tolerance-band based current controlled induction motor drives. Also in 1994 Hemati Hemati (1994) carried out the strange attractors in the Permanent magnet direct current drive by transforming the drives mathematical model into a Lorenz system. In 1997, Chau et al. Chau *et al.* (1997) analyzed the bifurcation and chaotic phenomena in a simple DC drive by taking the proportional gain and the supply voltage as bifurcation parameters.

Two years later in 1999, Chau et al. Chen *et al.* (2002) extended the nonlinear analysis to switched reluctance motor drives. In 2000, Suto et al. Suto *et al.* (2000) reported the period adding route to chaos in a hysteresis current controlled AC drive. In 2002, Li et al. Li *et al.* (2002) investigated the chaotic behavior in a permanent magnet synchronous motor (PMSM) by reducing the system model to a Lorentz system. In 2004, Gao et al. Gao and Chau (2004) reported the occurrence of a Hopf bifurcation and chaos in a synchronous reluctance drive. The paper showed that at some parameters of the drive, the attracting equilibrium point may lose stability and the trajectories begin to converge on a limit cycle.

Further variation of the parameter caused the trajectories to depart from the limit cycle and converge on a strange or chaotic attractor. In 2009, Dai et al. Dai *et al.* (2009) reported the Hopf bifurcation and chaos resulting from torus break down in a simple DC drive employing a PI controller. Due to the fact that the qualita-

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tive behavior of all nonlinear systems including electrical machine often changes when some of the system parameters are being varied, the nonlinear phenomena and chaotic behaviors in electrical machine are viewed as undesirable by most engineers and some work has been conducted on how to stabilize such systems Su and Li (2015); Kholerdi *et al.* (2016); Rajagopal *et al.* (2016) because chaotic oscillation in some electrical machine can affect their performance which can cause torque breakdown, oscillation with low frequencies and poor performance in speed control Rajagopal *et al.* (2016); He and Han (2017).

Among some control technique which have been applied for the stabilization of some electrical machine we can quote Pyragas with its method based on time delay approch Pyragas (1992, 2001), another's methods are based on nonlinear feedback control Ren and Liu (2006), sliding mode Cheng *et al.* (2011) adaptive back-stepping method Ge and Huang (2005) and active controller Cheukem *et al.* (2020). The previous method has been used to stabilize chaotic oscillation in some machine. In 2000, Asakura et al. Asakura *et al.* (2000) stabilize from the chaotic oscillation of an induction drive to stable operating point by applying neural network method. The disadvantage for many of the previous method is on the control time too long. The time delay approach Zhang *et al.* (2012) may force the system to operate in a desired periodic state. Despite the fact that it is not easy to find the delay in reality, this method can control the machine preserving the dynamic properties of the latter.

In this paper, the nonlinear chaotic phenomena in the steady state trajectories of IFOC of 3-phase induction motor were stabilized by applying delay feedback method comparing to sliding mode method to better show effectively of the choosing method. This technique is less complex than existing methods and was successfully applied to control chaotic behavior in IFOC of 3-phase induction motor. This work is structured as follows, after general introduction in section1, the mathematical description of IFOC of 3-phase induction motor and its numerical analysis are given in section 2. Section 3 deals with the chaos control while section 4 presents the electronic implementation of chaos control in IFOC of 3-phase induction motor. The last section is devoted to the conclusion.

HOPF BIRFUCATION IN IFOC

The IFOC can be described by the following rate-equations Kemnang Tsafack *et al.* (2020):

$$\frac{dx_1}{dt} = -C_1x_1 + \frac{k}{\tau r i_{sd}{}^*}x_4x_2 + C_2 i_{sd}{}^*, \tag{1a}$$

$$\frac{dx_2}{dt} = -C_1x_2 - \frac{k}{\tau r i_{sd}{}^*}x_4x_1 + C_2x_4, \tag{1b}$$

$$\frac{dx_3}{dt} = -C_3x_3 - C_4\left[C_5(x_1x_4 - x_2 i^*_{sd}) - T_L - \frac{C_3}{C_4}\omega_{ref}\right], \tag{1c}$$

$$\frac{dx_4}{dt} = (ki - kpC_3)x_3 - kpC_4\left[C_5(x_1x_4 - x_2 i^*_{sd}) - T_L - \frac{C_3}{C_4}\omega_{ref}\right]. \tag{1d}$$

where x_1,x_2,x_3,x_4 are respectively the direct and quadratic rotor flux component for the two first one and velocity for the third variable and the fourth is the quadratic axis stator current. Another parameters such as k, τ_r, $i_{sd}{}^*$, T_L , ω_{ref} represents respectively the ratio between the true value and the estimate value of rotor time constant, the rotor time constant, the reference current, the load torque and the reference speed. Figure 1 shows the bifurcation diagram of the variable, x_1 ,and it largest Lyapunov exponents (LLE) versus the parameter k.

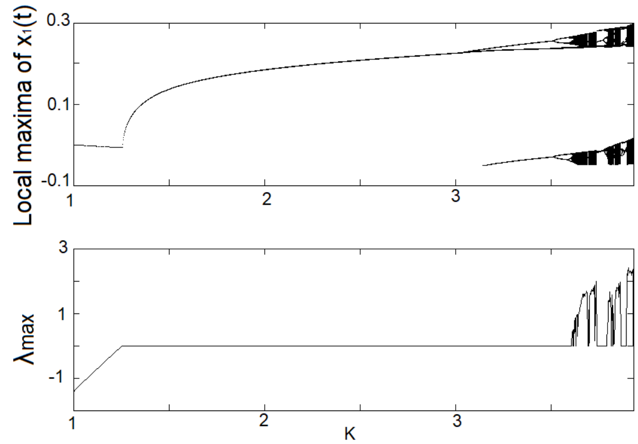


Figure 1 Bifurcation diagram depicting the local maxima of x_1 (a) and the corresponding LLE (λ_{max}) (b) versus the parameter k for C1=13.67, C2=1.56, C3=0.59, C4=1176, C5=2.86. M=0.069, ϕ_{ref}=0.4, $\frac{1}{\tau r i^*_{sd}}$=2.3581; TL=0.49, kp=0.01 and ki=0.5.

In Figure 1 (a), system (1) evolving to a steady state until $k \approx 1.3$, where there is appearance of the Hopf bifurcation followed by period 1 then 2 and so on. Fig. 1 (b) confirms the dynamical behavior found in Fig. 1 (a). The dynamical result of the machine (1) is illustrate when varying the parameter k in the range $1 \leq k \leq 4$, some phase portraits of system (1) are plotted in Fig. 2 for specific value of parameter k.

Steady state behavior and period-1-oscillations are presented in Figs. 2 (a) and (b) respectively while in Figs. 2 (c) to (f) chaos and period doubling are found.

CHAOS CONTROL IN IFOC USING SELF-CONTROLLER DELAY FEEDBACK

Chaos made IFOC of 3-phase induction motor unstable and should be controlled to keep secure operation. The simple self-control delay feedback method is used in this section to stabilize the chaotic behavior in indirect field oriented control of three phase induction machine due to its simplicity proposal controller for simple self-control delay feedback method is defined by:

$$u_1(t) = K_f\left[x_4(t-\tau) - x_4(t)\right] \tag{2}$$

where τ is the delay and K_f is the coupling strength. Our controller $u_1(t)$ is added to the equation (1d) of system (1):

$$\frac{dx_1}{dt} = -C_1x_1 + \frac{k}{\tau_r i_{sd}{}^*}x_4x_2 + C_2 i_{sd}{}^* \tag{3a}$$

$$\frac{dx_2}{dt} = -C_1x_2 - \frac{k}{\tau_r i_{sd}{}^*}x_4x_1 + C_2x_4 \tag{3b}$$

$$\frac{dx_3}{dt} = -C_3x_3 - C_4\left[C_5(x_1x_4 - x_2 i_{sd}{}^*) - T_L - \frac{C_3}{C_4}\omega_{ref}\right], \tag{3c}$$

$$\frac{dx_4}{dt} = (k_i - k_pC_3)x_3 - k_pC_4\left[C_5(x_1x_4 - x_2 i_{sd}{}^*) - T_L - \frac{C_3}{C_4}\omega_{ref}\right] + K_f\left[x_4(t-\tau) - x_4(t)\right]. \tag{3d}$$

A bifurcation diagram illustrating the dependence of the dynamical behavior of system (1) on the two parameters K_f and τ is plotted in Fig. 3.

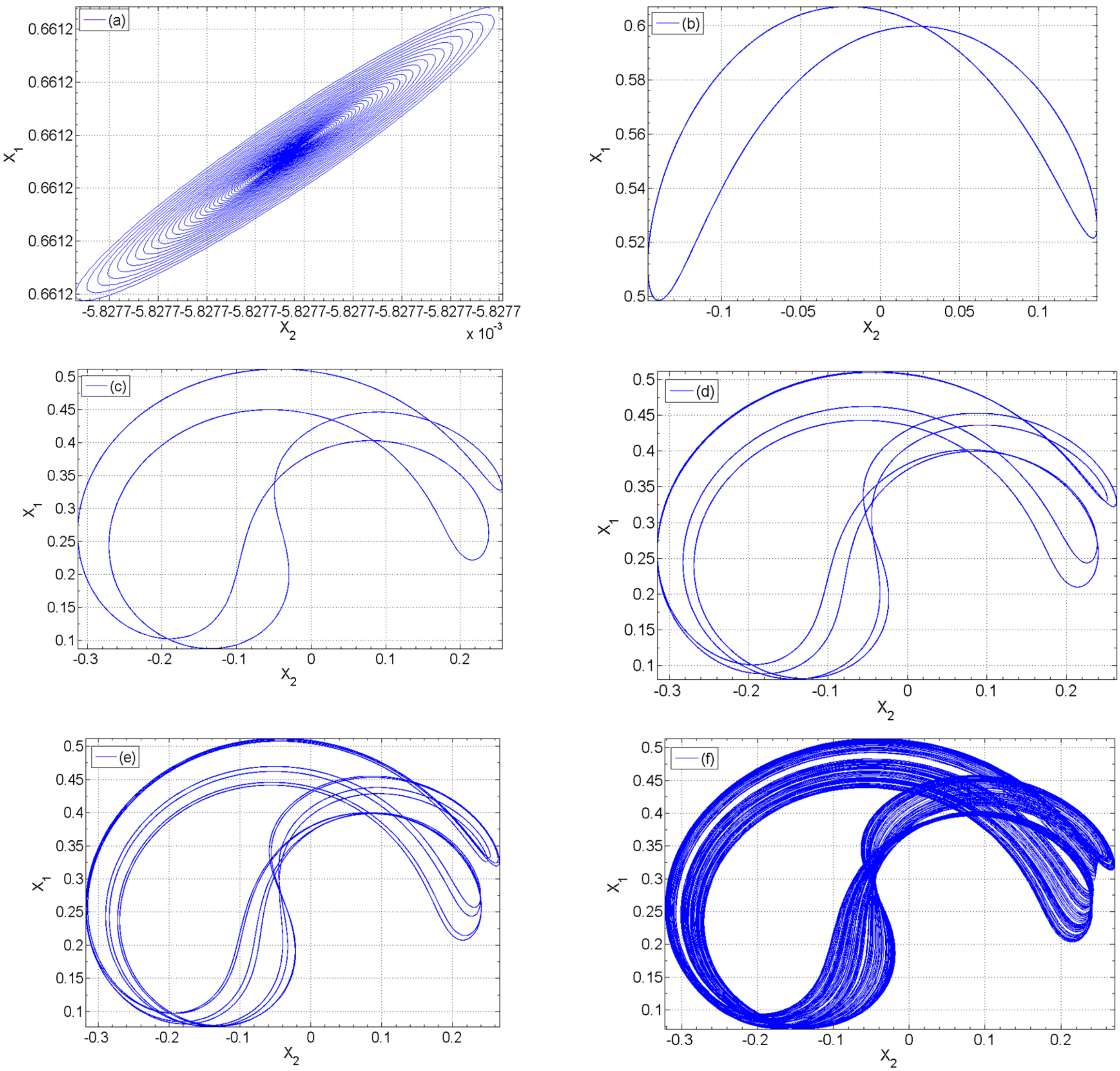


Figure 2 Phase portraits of system (1) in the plane (x2 , x1) obtained for some value of k :(a) k=1.2, (b) k=1.5, (c) k=3.2 , (d) k=3.56, (e) k=3.6 and (f) k=3.67. The initial conditions are (1,1,0.1,0.1) keeping the rest of parameters being identical to parameter of Fig.1.

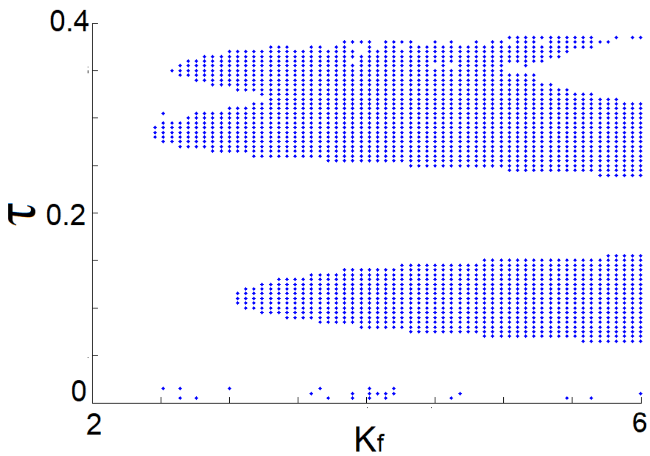


Figure 3 Regions of dynamical behaviors in the parameter space spanned by the two parameters K_f and τ for C_1=13.67, C_2=1.56, C_3=0.59, C_4=1176, C_5=2.86. M=0.069, ϕ_{ref}=0.4, $\frac{1}{\tau r i^*_{sd}}$=2.3581, T_L=0.49, k_p=0.01 and k_i=0.5. Periodic or steady state behaviors are in black dots and chaotic behaviors are in white dots.

System (3) can exhibit periodic behavior or steady state behavior or chaotic behavior depending on the parameters, K_f and ,τ , as presented in Fig.3. For, $K_f = 5$, the bifurcation diagram taking, τ as bifurcation parameter is presented in Fig. 4.

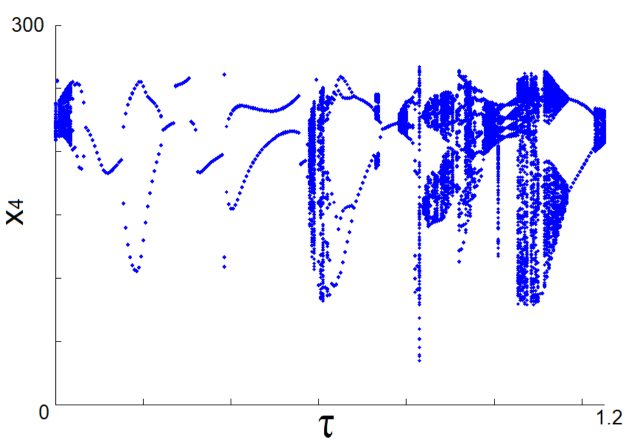


Figure 4 Bifurcation diagram of system (3) depicting the local maxima of x_4, versus the parameter, τ, for K_f=5, C1=13.67, C2=1.56, C3=0.59, C4=1176, C5=2.86. M=0.069, ϕ_{ref}=0.4, $\frac{1}{\tau r i^*_{sd}}$=2.3581; TL=0.49, kp=0.01 and ki=0.5.

In Figure 4, as the delay τ increases from zero to 1.2, the dynamics of system (3) alternates between a chaotic domain and a periodic domain. The phase portraits of system (3) illustrating the control of chaos in indirect field oriented control of three phase induction machine displayed in Fig. 5.

Scenario of controlling chaotic behavior toward periodic behaviors in system (3) by varying the delay τ and $K_f = 5$ is shown in Fig. 5. For,τ=0.5, bifurcation diagram of system (3) taking ,K_f as bifurcation parameter is shown Fig. 6.

From Figure 6, we observe a gradual exit from chaos by period doubling up to $K_f \approx 7.88$ where there is the appearance of Hopf bifurcation followed by steady state behavior. Therefore, the chaotic behavior found in IFOC of 3-phase induction motor can be controlled to periodic or steady state depending on the parameters K_f and τ. The phase portraits system (5) illustrating the control of chaos in IFOC of 3-phase induction motor is displayed in Fig. 7.

Scenario of controlling chaotic behavior toward steady state behavior in IFOC of 3-phase induction motor by varying the coupling strength K_f and the delay time τ=0.5 is shown in Fig. 7. To justify the choice of self-control delay feedback method, a sliding mode delay control method is used to control chaotic behavior IFOC of 3-phase induction motor. The sliding mode delay control method, the controller is defined by:

$$u_2(t) = K_f Sgn\left[x_4(t-\tau) - x_4(t)\right] \tag{4}$$

where the parameters τ and K_f are respectively the delay and the coupling strength. Our controller, $u_1(t)$,is added to the equation (1d) of system (1):

$$\frac{dx_1}{dt} = -C_1 x_1 + \frac{k}{\tau_r {i_{sd}}^*} x_4 x_2 + C_2 {i_{sd}}^* \tag{5a}$$

$$\frac{dx_2}{dt} = -C_1 x_2 - \frac{k}{\tau_r {i_{sd}}^*} x_4 x_1 + C_2 x_4 \tag{5b}$$

$$\frac{dx_3}{dt} = -C_3 x_3 - C_4 \left[C_5(x_1 x_4 - x_2 {i_{sd}}^*) - T_L - \frac{C_3}{C_4}\omega_{ref}\right] \tag{5c}$$

$$\frac{dx_4}{dt} = (k_i - k_p C_3)x_3 - k_p C_4 \left[C_5(x_1 x_4 - x_2 {i_{sd}}^*) - T_L - \frac{C_3}{C_4}\omega_{ref}\right] + K_f Sgn\left[x_4(t-\tau) - x_4(t)\right]. \tag{5d}$$

The bifurcation diagrams of systems (3) and (5) as function of the parameter,K_f, is plotted in Fig. 8 for, τ=0.5.

In Figure 8, the black dots represent the results obtained from system (3) when the control is non-adaptive and its shape given by $u_1(t) = K_f\left[x_4(t-\tau) - x_4(t)\right]$. While the red dots represent the results obtained from system (5) when the control law is given by $u_2(t) = K_f Sign\left[x_4(t-\tau) - x_4(t)\right]$. System (3) displays upside down period-doubling to chaotic behavior strew with periodic oscillation until $K_f \approx 7$ where there is appearance of Hopf bifurcation followed by steady state behavior. System (5) displays upside down period-doubling to chaotic behavior strew with periodic oscillation until $K_f \approx 7.46$ where there is appearance of Hopf bifurcation followed by steady state behavior. It is noted that system (3) has a larger periodic or steady state behaviors domain and smaller chaotic behavior domain compared to system (5) which has a smaller periodic or steady state behaviors domain and a larger chaotic behavior domain. Knowing that when the machine exhibits periodic or steady state behaviors it is working in a secure operation regime. Therefore, the simple self-control delay feedback method give better results in control of indirect field oriented control compared to the sliding mode delay control method.

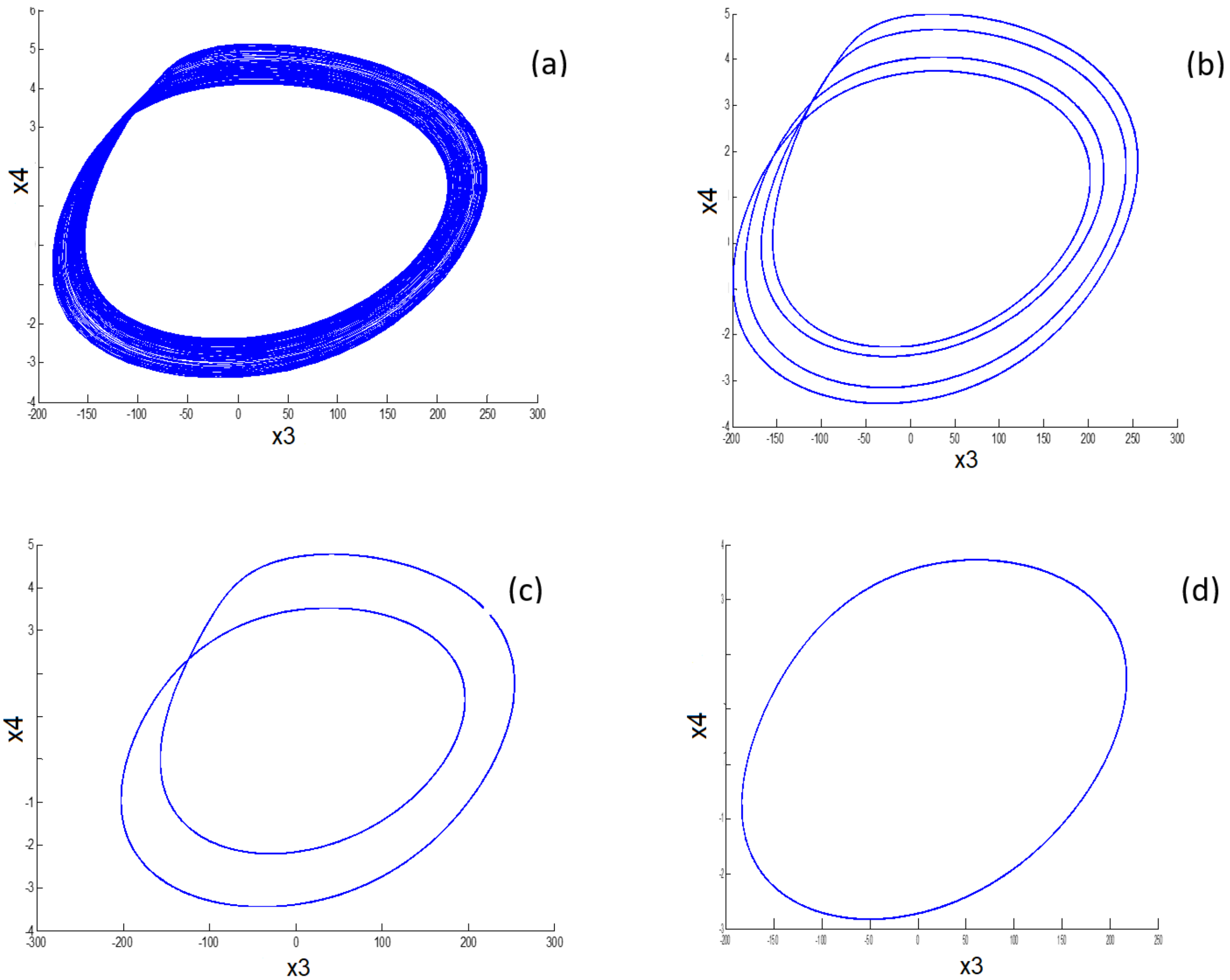


Figure 5 Portraits system (5) illustrating the control of chaos in system (3) for K_f=5 for specific value of delay,τ: (a) Chaotic attractor at, τ =0.025, (b) Period-4-limit cycles at, τ =0.67, (c) Period-2-limit cycles at, τ=0.7 and (d) Period-1-limit cycle at, τ =0.75. the figure is obtained by keeping the parameters as in Fig.4. and the initial conditions (1,1,0.1,0.1)

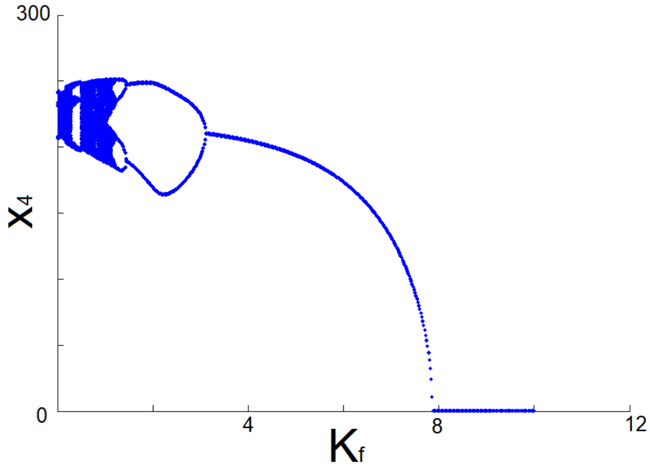


Figure 6 Bifurcation diagram of system (3) depicting the local maxima of x_4 versus the parameter, K_f for, τ=0.5, C1=13.67, C2=1.56, C3=0.59, C4=1176, C5=2.86. M=0.069, ϕ_{ref}=0.4, $\frac{1}{\tau ri^*_{sd}}$=2.3581; TL=0.49, k_p=0.01 and k_i=0.5.

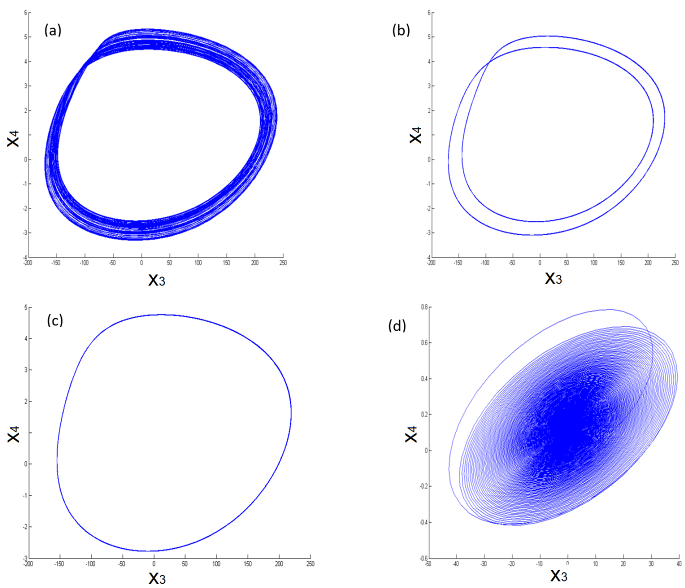


Figure 7 Portraits system (5) illustrating the control of chaos in IFOC of 3-phase induction motor of system (5) for, τ =0.5 for specific value of delay, τ: (a) Chaotic attractor at K_f=1.5, (b) Period-2-limit cycles at K_f=2, (c) Period-1-limit cycles at K_f=4 and (d) Steady state at K_f=7.88. The initial conditions are (1,1,0.1,0.1) and the rest of the parameters are the same as in the caption of Fig. 6.

ELECTRONIC IMPLEMENTATION OF IFOC USING SELF-CONTROLLER DELAY FEEDBACK

An alternative approach for exploring the controlled system (3) is the implementation of an electronic circuit. The circuit implementing the controlled system (3) is presented in Fig. 9.

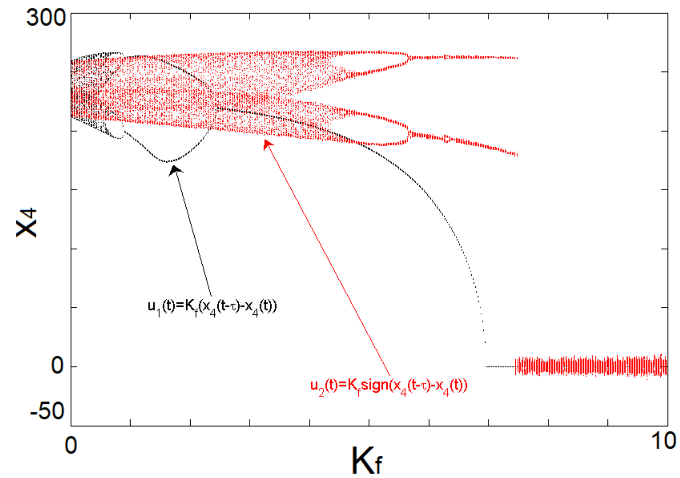
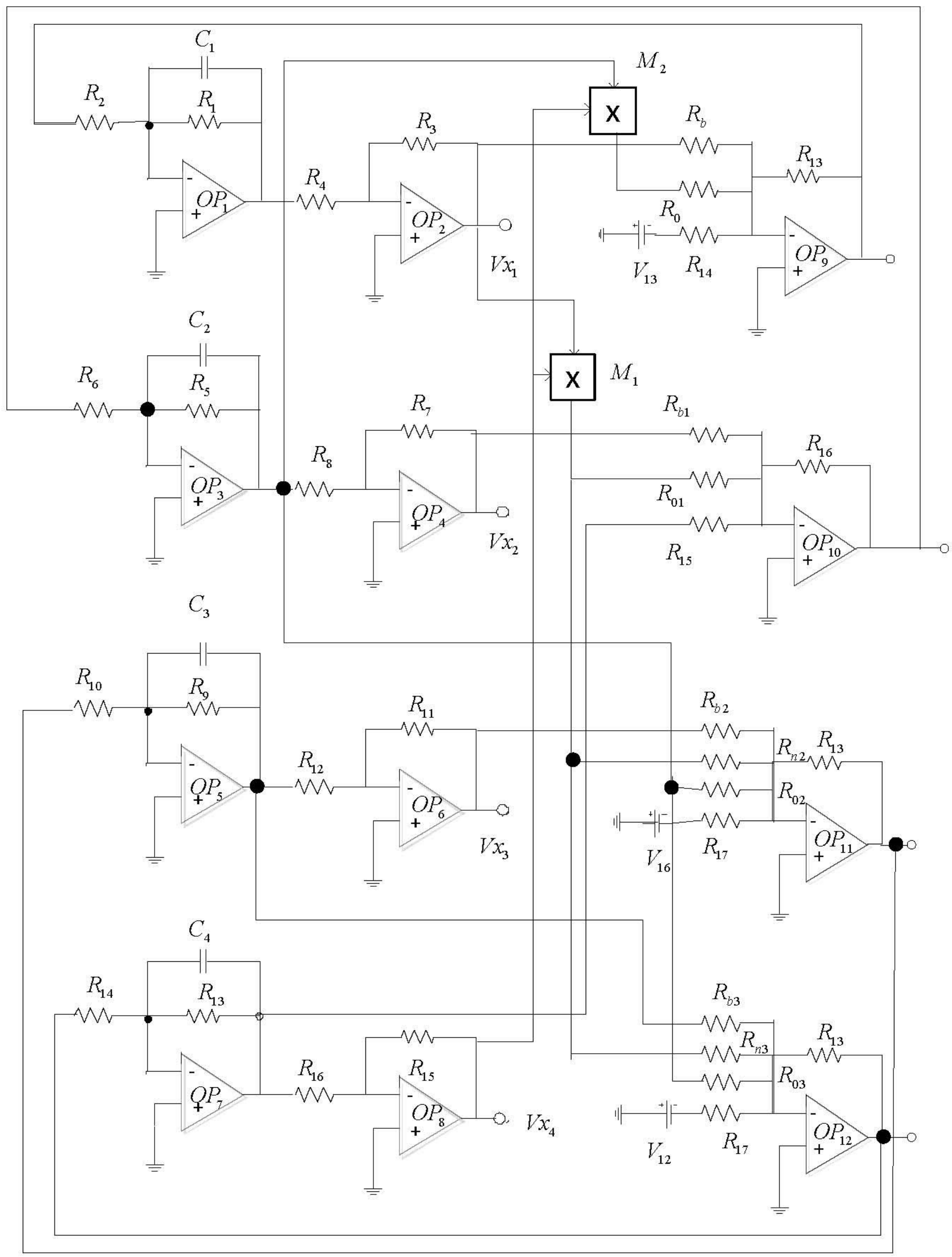


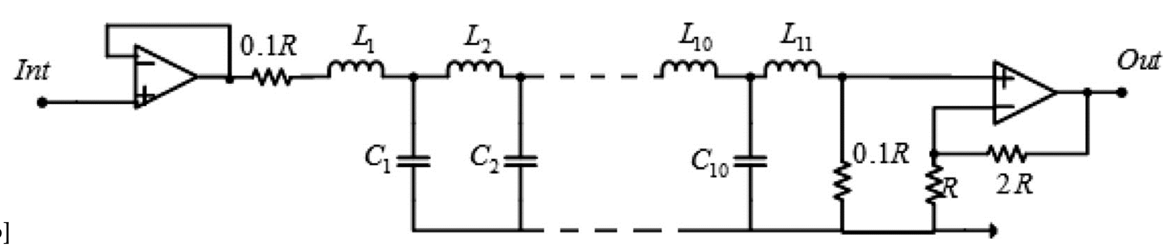
Figure 8 Bifurcation diagrams depicting the local maxima of x_4 versus the parameter, K_f for, τ=0.5, C1=13.67, C2=1.56, C3=0.59, C4=1176, C5=2.86. M=0.069, ϕ_{ref}=0.4, $\frac{1}{\tau ri^*_{sd}}$=2.3581; TL=0.49, kp=0.01 and ki=0.5.

The previous circuit is carried out with capacitors, resistors, operational amplifiers and analog devices. Parameters values are: $R_1 = 7.32,k\Omega$,$R_2 = 0.9,k\Omega$, $R_3 = 10,k\Omega$,$R_4 = 7.32,k\Omega$,$c = 10,nF$,R_5=0.9,$k\Omega$,R_6=6.41,$k\Omega$ R_7=169.5, $k\Omega$,$R_8 = 0.3,k\Omega$,$R =$ 10$k\Omega$,R_9=0.743$k\Omega$,$R_{10} = 10k\Omega$,$R_{11} = 20k\Omega$, $R_{12} = 29.73k\Omega$ $R_{13} = 212.59k\Omega$,$R_{14} = 10k\Omega$ $V_1 = 0.624V$,$V_2 = 0.6468V$,$V_3 =$ 6.468mV,ω_o=1000$rad.s^{-1}$, the phase portraits of controlled IFOC of 3-phase induction motor generated from circuit diagram of Fig. 9 are shown in Fig. 10.

From Figure 10, the matching of Pspice results with the numerical simulations results of Figs. 5 (a) and (d) and Figs. 7 (a) and (d) confirm the feasibility of the self-control delay feedback method.



[a]



[b]

Figure 9 [a] Circuit implementing the controlled system (3) and [b] Circuit implementing the time delay unit.

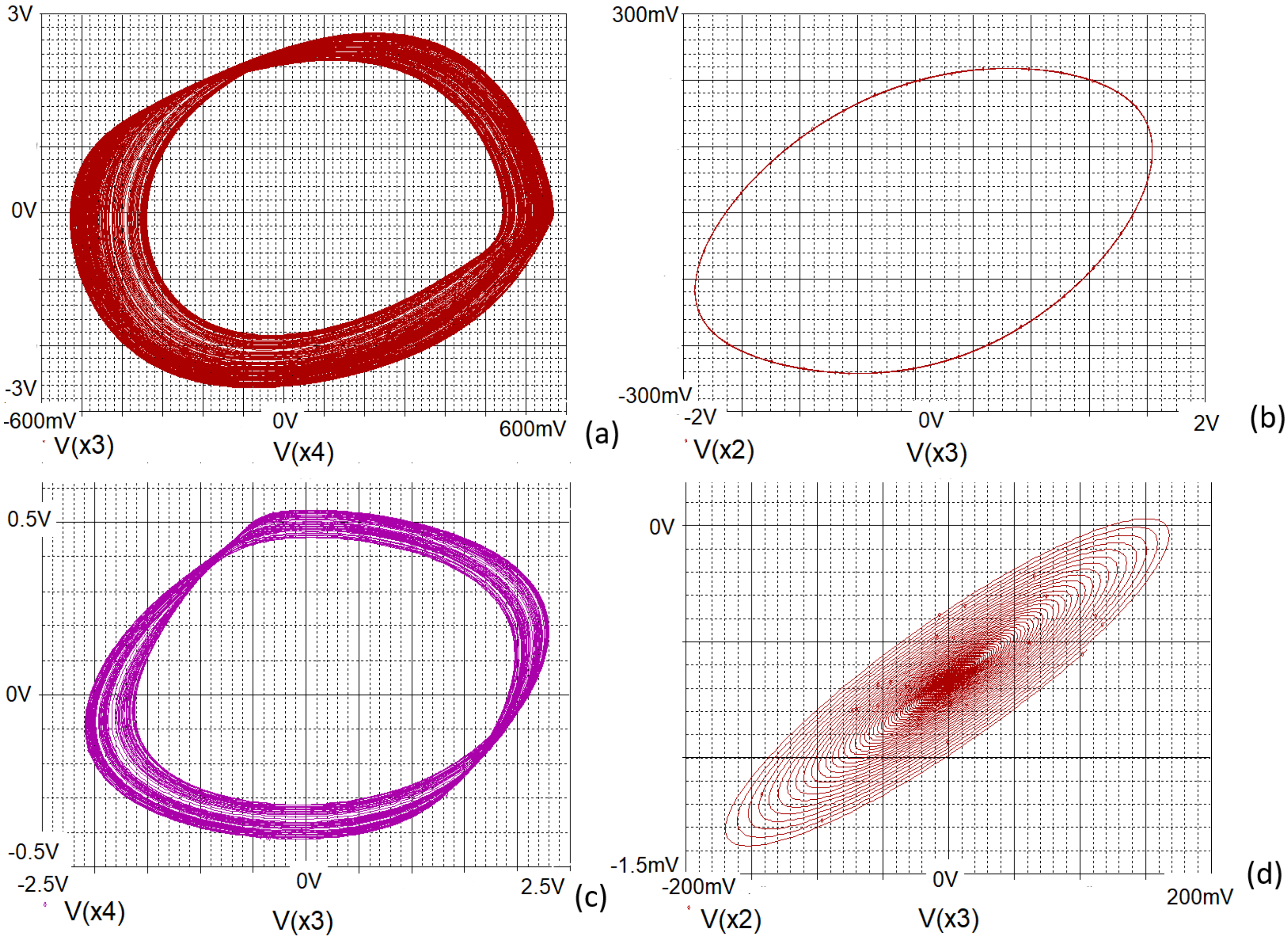


Figure 10 Phase portraits in (V_{X_1}, V_{X_2}) plane of the circuit in Fig. 8: (a) chaotic attractor for $R_n = R_{n1} = 0.6k\Omega$, (b) Period-1-limit cycle for $R_n = R_{n1} = 0.7k\Omega$, (c) chaotic attractor for $R_n = R_{n1} = 0.84k\Omega$ and (d) steady state behavior for $R_n = R_{n1} = 0.8k\Omega$. The initial values of capacitors voltage are $(V_{X_1}(0), V_{X_2}(0), V_{X_3}(0), V_{X_4}(0)) = (0.1V, 0.1V, 0.1V, 0.1V)$

CONCLUSION

This paper was devoted to dynamical behaviors and chaos control in indirect field oriented control of 3-phase induction motor. The numerical simulations revealed that this machine exhibits steady state behavior, Hopf bifurcation and period doubling bifurcation to chaotic oscillations with periodic oscillations windows. The two self-feedback delay controllers: A simple and a sliding mode delay controllers were designed to suppress the chaotic behaviors found in indirect field oriented control of 3-phase induction motor. Among these self-feedback delay controllers, the simple self-feedback delay controller is preferable because the controller suppress chaotic behavior in indirect field oriented control of 3-phase induction motor with a larger periodic or steady state behaviors domain and smaller chaotic behavior domain. Finally, the physical feasibility of simple self-feedback delay controller applied in indirect field oriented control of 3-phase induction motor was validated through electronic circuit's implementation on OrCAD-PSpice software.

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Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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