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Suppressing chaotic behavior in a top drive drilling system by means of fixed-time synergetic control

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Abstract

In this paper, the dynamics of an induction motor drive-based oil drilling system with a top drive is considered. The system model, consisting of an eleventh-order set of differential equations, is first derived. Then, its nonlinear dynamics are numerically investigated under variations of parameter values. Using this nonlinear model, the bifurcation diagram and the corresponding Lyapunov exponent spectrum are calculated, revealing undesired subharmonic periodic regimes and chaotic behavior for certain parameter values. The fixed-time synergetic control technique (FTSCT) is employed to stabilize the system toward a desired equilibrium point. The control strategy uses a macro-variable, defined as a linear combination of the speed error and the flux error of the induction motor. The results show that the FTSCT is effective in suppressing undesired oscillations.

Keywords Chaos · Top drive · Drilling string · Synergetic control · Fixed-time theory

1 Introduction

Oil exploration and extraction rely on specialized oil drilling systems. The two main parts of a drilling system are the mechanical section and the electrical section. The electrical part (top drive) consists of an electric motor and a gearbox, which provide the rotational motion to the mechanical section. The latter is composed of a series of special pipes connected to each other and, at the end, attached to a drilling bit. The schematic of the drilling system is shown in Fig. 1.

The mechanical section (drilling strings) is a highly nonlinear system due to the frictional impacts between the rocks and the drilling bit during the cutting operation, as well as the friction torque resulting from contact between the borehole and the pipes. This frictional force may cause complex nonlinear vibrations. Similarly, the IM and the AC drive that compose the electrical section are also strongly nonlinear. From the electrical perspective, the nonlinearity is due to the combination of two nonlinear parts: the IM and the AC inverter with a speed control governor.

Both sections of the drilling system are complex nonlinear systems and contain different parameters. Some of these parameters may vary during operation, human intervention, or aging. Such variations can lead to complex nonlinear oscillations in the drilling system. The oscillations in the dynamic of the drilling strings have been reported in several studies [1–10]. In particular, chaotic oscillations of the drilling string speed, driven by an IFOCIM system, have been reported in [11], where variations in certain parameter values lead to chaotic behavior.

Oscillations arising from bit–rock friction and the nonlinearity of the AC drive can lead to drilling string failure, increased wear, and bit damage—they also raise costs due to increased maintenance or lost time. In 1985, 45% of all drilling system problems were related to drill string failures, with average cost of about $106,000. Moreover, drill string failures occur in approximately 1 out of 7 drill rigs. In 1991, it was reported that Shell Expro drill string failures cost more than US $2 million in 2 months [12].

Therefore, the complex chaotic behavior of drilling systems must be controlled and stabilized. The control of chaotic

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