

# Nonlinear Model Predictive Controller for Kick Attenuation in Managed Pressure Drilling<sup>★</sup>

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**Abstract:** We propose a new design of nonlinear model predictive controller (NMPC) for automatic control of managed pressure drilling (MPD) system. The proposed controller acts in a pressure control mode and tracks bottom-hole-pressure (BHP) set point during normal operations, and automatically switches to a flow control mode in the event of abnormal situations, i.e. gas kick. It contains kick, when it occurs, within certain threshold by the deft use of nonlinear state constraints. We use output feedback control architecture and employ offset-free NMPC algorithm which utilizes recursive-discretization for discretization of the model and use active set method for optimal control calculation. We demonstrate that the proposed controller is able to track a bottom hole pressure set point and contain influx in the presence of measurement noise and plant model mismatches.

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## 1. INTRODUCTION

Managed pressure drilling (MPD) is an overbalanced drilling technique (Malloy et al., 2009) in which the bottom hole pressure is regulated by employing an automated choke manifold. The advantages of MPD are enabling the drilling of so-called *undrillable wells* in which pressure window is very narrow and ensures safer handling of reservoir influx. There will be an influx of reservoir fluids called *kick* when the bottom hole pressure  $p_{bh}$  is less than the reservoir pressure  $p_{res}$ . If a kick is unmitigated, large quantities of reservoir fluids may flow to the surface endangering people and the environment. The traditional method to handle a kick requires drilling to be stopped and the annulus needs to be shut-off and that contributes to the non-productive time (NPT). MPD has the potential to reduce NPT and enhance safety. It was reported in (Vieira et al., 2008) that without MPD it took 65 days to drill a particular well while using MPD it took only 45 days. There is potential to reduce NPT further through automatic pressure management and automation usually leads to enhanced safety. Automated MPD solutions range from automating conventional well control methods to model based control of pressure and flow rate. An extensive review of computer control in managed pressure drilling can be found in (Nikolaou, 2013). Control requirements for MPD system was discussed in (Godhavn et al., 2010), a simple PID

controller was used to track a choke pressure setpoint and simulation results for pipe extension sequence was shown and it was suggested that gain scheduling can be used for tackling nonlinearities. Instead of gain scheduled PID, a nonlinear controller for BHP regulation was designed in (Godhavn et al., 2011) using feedback linearization technique and tracking of BHP setpoint was enabled by a BHP estimator. Large kicks still require that drilling be stopped, so that kick can be handled by conventional kick handling method. In order to improve safety during such operations, in (Carlsen et al., 2013) PI, IMC, and MPC pressure controllers were designed to automate kick handling sequence. In (Nandan et al., 2014), a robust  $H_\infty$  loop shaping controller was designed for handling variations in mud density, well length, and mud flow rate. For severe changes in the flow rate and choke opening, gain switching robust controller was suggested. The advantage offered by pressure control is its ability to track a BHP setpoint but during a kick, continued pressure setpoint tracking will not attenuate a kick (Zhou et al., 2011). For kick attenuation flow controllers have been designed. Feedback linearised flow controllers were presented in (Hauge et al., 2012) and (Hauge et al., 2013). The choke opening was used to regulate the exit flow rate and thereby the in/out flux. An in/out flux and estimator was also presented in (Hauge et al., 2012) and (Hauge et al., 2013) they also estimate bit flow rate. In (Santos et al., 2003), a well control method which involves comparing the in/out flow rates for detecting kicks and remedying by increasing the back pressure was presented. Flow control is an effective strategy for

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suppressing kicks but typically in an MPD operation BHP must track a set point. In (Zhou et al., 2011) a switching controller which works as a pressure controller during normal operation and as a flow controller while handling kicks was presented. In order to perform overbalanced drilling, reservoir pressure estimates are required, in (Zhou et al., 2011) a nonlinear passivity based observer for reservoir pressure and kick estimation was developed. A nonlinear pressure/flow switching controller was designed for dual gradient drilling (DGD) in (Zhou and Nygaard, 2011). DGD is a variant of MPD in which muds of varying densities are used and as a result the hydrostatic pressure is piece-wise linear. Nonlinear controllers depend heavily on tuning and necessary expertise might not be available for upstream operations. Model predictive controller (MPC) and nonlinear MPC design have also been considered for MPD, they are well suited for MPD because their ability to handle constraints and nonlinearity respectively. An NMPC scheme for control of underbalanced drilling (UBD) was developed in (Nygaard and Nævdal, 2006). BHP was regulated by computing optimal choke opening in receding horizon fashion. A two phase model of drilling well was used as an UBD well produces hydrocarbons while drilling. In (Breyholtz et al., 2009) NMPC was used to coordinate pump flow rate and choke opening in order to control BHP. The control was evaluated for pressure regulation during pipe extension sequence but control of kicks were not treated. In (Breyholtz et al., 2010), linear MPC control of DGD was considered. The bottom hole pressure and hook position were controlled by manipulating main pump and sub sea pump flow rates as well as the drill string velocity. The focus of the study was on optimal movement of drill string in order to minimize pressure variations. Work done in (Breyholtz et al., 2010) was further expanded in (Breyholtz et al., 2011), robustness and results in presence of noise was analysed. Use of linear MPC was considered in (Møgster et al., 2013) which utilized step response models between the inputs, namely the mud flow rate and choke opening, and the outputs namely the bottom hole pressure and the pressure at the casing shoe. The controller was implemented using Statoil's in-house MPC software SEPTIC. The innovation was in manipulating pressure at two points, BHP and pressure at the casing shoe, but its effectiveness in dealing with kicks and severe drop in pumping rate was not studied. In (Pedersen et al., 2013) UBD control was performed by using First Order Plus Time Delay (FOPTD) models. The bottom hole pressure and return flow rate were regulated by manipulating the choke opening and mud pump flow rate. Regulating outlet flow will be useful in UBD as it produces during drilling. But an MPD well, the kind of well considered in this work, produces only during a kick and at other times a BHP set point has to be tracked hence that requires setting the NMPC problem differently from that in (Pedersen et al., 2013). In (Mahdianfar et al., 2013) a joint unscented Kalman filter was developed for state and parameter estimation as frictional losses and annular geometry are uncertain and estimation of those parameters will improve control solutions. Thus for kick rejection switching pressure/flow controller offers the best solution and NMPC is very well suited for MPD because of its ability to handle constraints and nonlinearities. We make use of NMPC technique to implement the switched

pressure/flow control philosophy. The controller presented in this paper has the following features: The NMPC operates as a pressure controller which tracks BHP under normal drilling conditions. The controller acts more like a flow controller when a kick occurs and contains a kick within a tunable threshold. The controller is able to work under different mud flow rates and choke opening without any deterioration in performance. The designed NMPC controller is able to perform well under persistent disturbance, plant model mismatch, and noisy measurements. The controller is able to regulate bottom hole pressure during pipe extension sequence as well.

## 2. SYSTEM DESCRIPTION

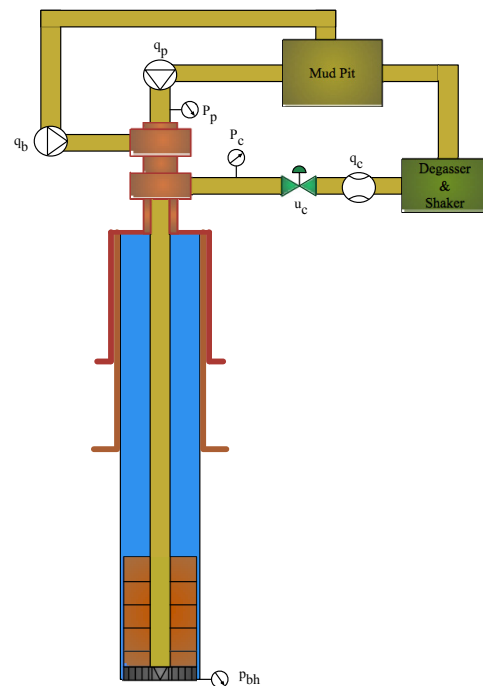


Fig. 1. Schematic representation of managed pressure drilling

The MPD process consists of two control volumes, the drill string and the annulus. The schematic representation of MPD process is shown in Figure 1. The drilling mud is pumped into the drill string under pump pressure  $p_p$  and at flow rate  $q_p$ . The mud exits the drill string through the drill bit at a flow rate  $q_{bit}$ . The drilling mud then flows through the annulus control volume and exists it through a choke at pressure  $p_c$  and flow rate  $q_c$ . The pump pressure, choke pressure, and bit flow rate are given by Equations (1), (2), and (3) respectively.  $\beta_d$  and  $\beta_a$  are bulk moduli of mud in drill string and annulus respectively.  $\rho_d$  and  $\rho_a$  are the mud densities in the drill string and annulus respectively.  $V_d$  and  $V_a$  are the volumes of the drill string and the annulus respectively.  $M$  is a mass like property. The pressure at the bottom hole  $p_{bh}$  is given by Equation (4). The flow through the choke is given by Equation (5) where  $u_c \in [0, 1]$  is the choke opening. The kick flow rate  $q_k$  is given by Equation (6).  $f_d$  and  $f_a$  are frictional loss coefficients in the drill string and the annulus respectively which relate volumetric flow rate and frictional pressure drop. Due to the addition of reservoir fluids and cuttings in the annulus,

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