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# Optimal Ammonia Injection for Emissions Control in Power Plants

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**Abstract:** One of the effective devices to reduce $NO_x$ in power plants is the ammonia based selective catalyst reduction (SCR) system. In this paper, kinetic SCR model simulator is tuned and validated with representative site data from an actual combined-cycle power plant. This simulator is then used for the development and implementation of model predictive control (MPC) for SCR systems to control the plant startup $NO_x$ emissions along with maintaining ammonia slip within the acceptable limit. Also, the results of linear and nonlinear MPC are compared. The startup $NO_x$ reduction obtained in both cases is seen to be close to ~85%, but the computational effort required for both these approaches differ significantly.

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Keywords: Multivariable control, model predictive control, combined cycle power plant, selective catalyst reduction, model validation, linearization, emissions control.

## 1. INTRODUCTION

### 1.1 Background

Combined-cycle power plants operating on the Brayton cycle for gas turbine and the Rankine cycle for steam turbine; with natural gas and water as working fluids respectively; achieve efficient and economic power generation. Flexibility provided by these systems make them attractive for both utility power generation and industrial cogeneration applications.

Over the last decade, demand of energy has continued to increase. Due to higher efficiency of combined-cycle power plants (>60% at base load ISO conditions), they are preferred over other types of conventional power plants. However, with their growing numbers and increasing requirement for flexible operation (i.e. frequent load change, startup and shutdown), their emissions concentrations have been increasing, leading to a negative impact on the environment. Hence, the emissions standards are becoming more and more stringent; especially during the transient operations of these systems; and are likely to continue towards zero emissions-level in the future. Power plant emissions are usually measured at the stack using continuous emissions monitoring systems (CEMS). The CEMS data typically includes measurements on $CO_2$, $NO_x$, and $NH_3$ emissions at the stack outlet. These emissions regulations are typically met by using after-treatment systems such as an SCR, which is widely used due to its efficiency and selectivity for $NO_x$ removal.

The SCR system is used in the heat recovery steam generator (HRSG) of a power plant, to chemically reduce $NO_x$ emissions from the turbine exhaust gases by converting them into environmentally neutral nitrogen and water via its reaction with injected ammonia ($NH_3$). $NH_3$ injection rate if not adjusted optimally can lead to either higher $NO_x$ emissions or unreacted $NH_3$ emissions known as $NH_3$ slip. $NH_3$ storage on catalyst surface must be carefully managed to maximize $NO_x$ conversion efficiency while minimizing $NH_3$ slip. Hence, different control strategies have been suggested in the past to control $NO_x$ emissions with optimal $NH_3$ injection. This paper proposes one such control strategy based on MPC, along with simulation results using the suggested technique.

### 1.2 Literature Review

Different control strategies have been used in the past for SCR control. Schär & Christoph (2003) showed feedforward control to be effective for optimal $NO_x$ removal and limited $NH_3$ slip when no disturbances enter the process. The feedforward loop was developed for $NO_x$ control, with constant NH3 slip and $NO_x$:$NH_3$ slip ratio. The results showed that the feedforward strategy worked well but resulted in excess NH3 slip using the constant NH3 slip setpoint control. Next, a feedback controller was used to improve the transient response as well as reduce the effects of few sources of error like the error between estimation of $NO_x$ concentration and actual $NO_x$ at the outlet, error between desired and injected amount of NH3 in order to obtain proper amount of NH3 injection for $NO_x$ reduction, deterioration of catalytic activity due to aging, etc. The feedback also adds a control delay to the system. A cascaded control structure was also implemented which works well at high percentage of base load, but is not effective during startup or shutdown. Another approach by Willems & Cloudt, (2011) showed an NH3 sensor-based $NH_3$ slip control strategy for SCR system. This control strategy was validated for 30% urea under and over dosage, and showed excellent results in avoiding $NH_3$ slip while maintaining high $NO_x$ conversion. Also, a comparison between $NO_x$ and $NH_3$ sensors-based strategies was shown to conclude that the use of $NH_3$ sensors, instead of $NO_x$ sensor, provides better results for European transient cycle. Another

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paper by Meisami-Azad, et al. (2010) implemented a state/output feedback controller using linear parameter varying (LPV) design for urea-SCR reduction after-treatment system. Feedback control using state observer was shown to require more computational effort compared to strategy based on sensor feedback only. Hsieh, et al. (2010) proposed an extended Kalman filter (EKF) based observer to estimate the NH3 catalyst coverage ratio and storage capacity. As NH3 coverage ratio affects the SCR $NO_x$ conversion and NH3 slip, and there is no conventional sensor available for measurement of same, model-based estimation plays an important role here. The simulation results showed that their proposed EKF gave good estimations for slow as well as fast time varying NH3 storage capacity models. Shen, et al. (2011) showed that a variable structure controller ensures robust $NO_x$ emissions and $NH_3$ slip control within limits.

Advanced control strategy such as MPC has also been implemented previously to SCR systems in real-time by linearizing the nonlinear SCR model as shown in Chiang, et al. (2010). MPC was able to maintain $NO_x$ conversion efficiency and minimize $NH_3$ slip. During the Federal test procedure (FTP) for transients, it was seen that $NO_x$ conversion efficiency of 93% was achieved and NH3 slip was maintained at an average value of 10 ppm. Another MPC application was shown by Zhang, et al. (2014) for two small urea-based catalyst cans of equal volumes in a diesel engine. NH3 coverage ratio on the catalyst of these cans was optimized using nonlinear MPC with a stiff nonlinear SCR system model. As it was difficult to discretize the stiff nonlinear system with a fixed sampling period, a nonlinear MPC (NMPC) optimization algorithm with interpolation in the manipulated variable adjustments and fixed-point constraint was proposed. The optimization problem with state and input constraints for different initial values of NH3 coverage ratios was solved. The NMPC solution was shown to reduce $NO_x$ while satisfying the pre-set constraints.

An MPC solution based on a reduced-order nonlinear model was introduced in McKinley & Alleyne (2012). Successive linearization of model, analytical solutions and varying cost function lead to significant reduction in computational effort. A gradient-based parameter adaptation law for a dozer scale factor (ratio of actual to commanded aqueous urea injection rate) was employed in order to achieve desired performance. The paper also showed that the feedback approach offers significant robustness over a feedforward control approach in responding to plant uncertainty. The suggested adaptive MPC method also demonstrated reduced variability in performance under changing operating conditions depending on FTP cycle.

In this paper, we have briefly described the SCR system in power plants and the kinetic model developed for it. Also, the simulation results using LMPC and NMPC are shown on startup emissions, and computational burden using the two approaches are compared. The paper is structured as follows: section 2 gives system and model description, section 3 discusses the solution strategy, section 4 shows the results, and the paper is concluded in section 5.

## 2. SYSTEM AND MODEL DESCRIPTION

### *2.1 SCR System*

SCR is widely used in internal combustion engines and power plants as an exhaust gas after-treatment system to curb $NO_x$ emissions. In internal combustion engines, another type of after-treatment system used is lean $NO_x$ trap (LNT), Hsieh, et al. (2011), which traps $NO_x$ from the engine exhaust gas and stores it in a solid form. As the storage capacity of catalyst is finite, it needs to be purged at regular intervals by injecting more fuel, which is undesired. Hence, SCR, which uses $NH_3$ or urea as a reductant, is usually a more preferred choice for the after-treatment system. However, SCR can show stack or tailpipe $NH_3$, especially during transient operations, which needs to be constrained within limits. Thus, constraining this outlet $NH_3$ while sufficiently dosing $NH_3$ to reduce and maintain $NO_x$ under limits is a challenging operational control task, particularly during transients.

When used in a combined-cycle power plant, SCR is typically located in HRSG after the CO catalyst, where temperature is ideal for $NO_x$ reduction. The SCR system uses a catalyst (vanadium- or zeolite-based) on which NH3 is injected. NH3 is typically vaporized by hot flue gases or by using an in-line air heater before being injected in the HRSG using multiple nozzles. This aqueous NH3 reacts with $NO_x$ during passage through the catalyst and reduces it to nitrogen and water. Typically, the $NO_x$ reduction efficiency increases with increase in NH3 to $NO_x$ ($NH_3$ : NOx) ratio within the catalyst. But, if this ratio becomes too high, unreacted NH3 passes through the reactor and appears in the stack as NH3 slip. Hence, tight control is needed to reduce $NO_x$ and $NH_3$ slip in the exhaust.

### *2.2 SCR Model*

Much research has been done in past on SCR modelling and its control. A one-dimensional SCR model was developed by Shost, et al. (2008) and used for real-time control of aqueous urea dosing on catalyst. A feedback loop was also implemented using $NH_3$ sensor to meet $NO_x$ emission requirements and $NH_3$ slip limits. A model for zeolite catalyst was developed, and comparison between vanadium and zeolite catalysts was done by Chatterjee, et al. (2007). The vanadium catalyst gives better $NO_x$ reduction at lower temperatures, whereas, zeolite gives better $NO_x$ reduction at higher temperatures. For power plants, typically Vanadium-based catalysts are used due to its suitability for the higher operating temperatures of SCR, placed in the HRSG. A model used in this paper is also a 1-D dynamic model considering all the key reactions taking place in SCR as described below:

$NH_3$ adsorption:

$$NH_3 + \theta_{avg} \rightarrow NH_3.\theta_{avg} \tag{1}$$

$NH_3$ desorption:

$$NH_3.\theta_{avg} \rightarrow NH_3 + \theta_{avg} \tag{2}$$

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