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Online optimal control schemes of inlet steam temperature during startup of steam turbines considering low cycle fatigue

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ABSTRACT

Great thermal stresses and fatigue damages will be developed during the startup of steam turbines, which will threaten the safety of operation. To save energy and improve the flexibility of the power unit, inlet steam temperature of steam turbines should be controlled online in an optimal way. A new method to obtain online optimal control schemes of the inlet steam temperature considering low cycle fatigue is presented in this paper using the Green's Function Method and the Pontryagin's Maximum Principle. New analytical models of temperature and thermal stresses are proposed. For a hot startup, constant material properties are used and the steam temperature history that can maintain maximum Von Mises stress close to the permitted value is proved to be the optimal control scheme. For a cold or warm startup, the optimization thermal stress considering temperature dependent material properties is found to be determinated by material properties and Green's functions, which may not be equal to the maximum permitted value. Application of the proposed method to the cold start-up process of a 600 MW steam turbine is introduced. Compared with the conventional start-up scheduling, the proposed optimal control scheme can shorten the time of startup greatly without exceeding permitted fatigue damage.

1. Introduction

Nowadays steam turbines are increasing single-machine capacity and often operated at variable load and with several stops to meet the user demand, satisfy the CO_2 emission limits and maximize profits [1]. Growth in both capacity and operation complexity of turbines demands advances not only in machine design, but also in plant control schemes and systems. To save energy and improve the flexibility of the power unit, an important topic in plant control systems is finding a way to reduce the time of startup without shortening the machine lifetimes and exceeding the environmental restrictions [2]. Optimal control problems of steam temperature during the startup of a power plant considering thermal stresses have been discussed for a boiler [3] and a boiler evaporator [4].

For a steam turbine, the inlet steam temperature will change in a large range during the startup, which will develop great thermal stresses and fatigue damages in turbine components [5]. One of decisive factors for the quick startup of a steam power plant is thermal stresses and fatigue damages developed in the turbine components. Since the online control of inlet steam temperature can be easily implemented by suddenly injecting cooling water, the design of optimum control schemes of inlet steam temperature is the key for a quick startup.

The optimum control schemes of inlet steam temperature can be obtained based on off-line scheduling and on-line control methods. The off-line scheduling method can provide start-up schedules before turbines are put into operation based on life predistribution schemes, which will recommend inlet steam temperature rising curves and give inlet steam temperature rising rate limits during the startup [5]. In Ref. [6], a method has been presented to evaluate the effect of the current operation schedules in terms of reduction of residual life. In Refs. [7,8], the process dynamic simulation models were obtained by using finite volume solution method and finite difference solution method to solve one-dimensional partial differential equations, which enabled the dynamic simulation of failure analysis, design and verification of start-up procedures.

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Though off-line scheduling method can provide optimum start-up schedules, it is a fact that the real operation conditions of turbines are complicated and online inlet steam temperature might be different with those assumed offline during the startup. Thus, online optimum control schemes should also be developed based on online parameters measured. There are two key problems for the design of the online optimum control schemes of inlet steam temperature: (1) the method to obtain online information of thermal stresses and temperature in turbine components accurately and quickly; (2) the method to find online optimum inlet steam temperature history.

The accuracy of thermal stresses and temperature in turbine components during the startup has great effect on the efficiency of online optimum control schemes of inlet steam temperature. If thermal stresses and temperature in turbine components are not calculated accurately and quickly, the online optimum control schemes of inlet steam temperature obtained are meaningless.

It is difficult to obtain online information of thermal stresses and temperature by measurement for turbine components during operation, especially for rotors. Considering the complex shape of turbine components, some researchers use finite element model(FEM) to obtain thermal stresses and temperature in turbine components [9]. FEM is a powerful tool and can provide accurate information of thermal stresses and temperature because the complex shape of turbines and temperature dependent material properties can be considered. However, due to the huge volume of a steam turbine, FEM is too time consuming and it is difficult to get online optimum control parameters by using FEM.

Simplified analytical expressions of temperature and thermal stresses in one-dimensional axis-symmetry cylinders [10] and two-dimensional axis-symmetry cylinders [11] are not suitable for steam turbines since the geometry of a steam turbine is complicated. Some researchers had investigated the online optimum control problem of turbine components to find the optimum startup schedule based on actual operation data by the neural network method [12]. The neural network method can use network and fuzzy rules to determinate the optimum inlet steam temperature directly if there is a direct correlation between the measured inlet steam temperature and thermal stresses [13,14]. However, this method needs a great deal of engineering power to prepare the fuzzy rules and the knowledge since the accuracy of this method is directly related to the numbers of training samples and neuron units of network [12]. Also, this method cannot provide the explicit relationship between thermal stresses and inlet steam temperature, which is difficult to obtain online optimum control schemes by using optimal control theory. Green's Function Method(GFM) is a better way for online calculations of temperature and thermal stresses with the assumption of constant material properties [15,16]. In Ref. [12], A GFM algorithm is proposed to calculate and control stresses in rotors and casings of turbines with the assumption of constant material properties. Unfortunately, if steam temperature changes in a large range, e.g., during cold or warm startup, temperature dependent material properties should be considered [17]. At present few researches has discussed the effects of temperature dependent material properties on optimum control schemes.

Generally, the aim of optimum control schemes was to find the optimum inlet steam temperature history for a start-up operation. The optimization method used is important and should provide optimum temperature history which can assure that the life loss of turbines remains within permitted limits and the process is shortest. However, in almost all of the investigations mentioned above, the aim was simplified to find the optimum steam temperature history that can maintain maximum total stress close to the permitted value. This simplified aim is proposed by experiences, which should be proved by using an optimal control theory first if it is true. Otherwise, new optimum control schemes of inlet steam temperature should be proposed based on an optimal control theory.

Thus, from the above discussions, though many researchers have investigated online optimal control schemes of inlet steam temperature, the following two basic questions still need to be solved: (1) If the assumption of constant material properties can be used, whether the aim of finding the optimum steam temperature history that can maintain maximum total stress close to the permitted value is true should be proved; (2) How to deal with the effects of temperature dependent material properties on the design of optimal control schemes. These two problem are very important, but at present few researches has discussed them.

This paper aims to solve these two questions and propose new online optimum control schemes of the inlet steam temperature based on GFM and Pontryagin's Maximum Principle [17]. New analytical models of temperature and thermal stresses are proposed to meet the requirement of the design of online optimal control schemes by using GFM. For the cases of constant material properties and temperature dependent material properties, optimum parameters are determined and proved by using the proposed calculation models of thermal stresses and the Maximum Principle. The effects of temperature dependent material properties on the design of optimal control schemes are investigated. Application of the proposed method to the cold startup process of a 600 MW steam turbine is introduced.

2. Selection of state variables and control variables

The aim to optimize the start-up process of steam turbines is to reduce time considering the constraint of low cycle fatigue. The major factor that affects the low cycle fatigue life of steam turbines is the fluctuations of inlet steam temperature. Thus, the optimal control schemes of inlet steam temperature should be obtained considering the constraint of low cycle fatigue.

To calculate low cycle fatigue, elastic plastic analysis needs to be done. Since fully elastic plastic analyses are complex and time consuming, the simplified elastic plastic analysis which relies on elastic analyses and the application of an appropriate correction for plasticity effects is often used for fatigue analysis [18]. In this way, elastic stress analysis can be used for the calculation of the fatigue usage factor and the constraint of low cycle fatigue can be transformed into the constraint of elastic thermal stress.

It is neither possible nor necessary to calculate and control the thermal stress and fatigue for all of turbine components. For steam turbines, usually possible hot spot positions are on the surface of rotors.

Thus, the inlet steam temperature is taken as the state variable and elastic thermal stresses at hot spots on the surface of a steam rotor is taken as the control variable for the optimal control schemes during the start-up process.

3. Design of optimal control schemes

To obtain the optimum control schemes of inlet steam temperature during startup, the first step is to calculate thermal stresses at hot spots accurately.

The temperature distribution in turbine rotors meets the following nonlinear differential equation during startup: