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Procedia Engineering 186 (2017) 592 – 600

Procedia Engineering

www.elsevier.com/locate/procedia

XVIII International Conference on Water Distribution Systems Analysis, WDSA2016

State Estimation for Water Distribution Networks in the Presence of Control Devices with Switching Behavior

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Abstract

In process monitoring and control, state estimation is the fundamental tool for processing redundant and noise-corrupted measurements in order to provide reliable estimates of the state of a system. In the context of water distribution networks (WDNs), state estimation has been proposed as the core technology which can enable various applications ranging from real-time monitoring and control to anomaly diagnosis, such as leak detection and localization. Measurements are typically available from sparse and often scarce telemetry sensors, such as flow at the inlet of a district metered area (DMA) and pressure at some nodes, or from utility estimates, for example prior estimates of the nodal demands. The problem consists of using the available measurements to reconstruct an estimate of the state variables and is solved iteratively by minimizing the weighted least squares (WLS) of the differences between the measurements and model predictions, typically with gradient methods. WDN state estimation in the presence of control devices, such as pressure reducing valves, remains an open problem due to the complexity in modeling efficiently their switching behavior. Control elements prevent from obtaining an explicit function of the measurements with respect to the state variables for all possible switching statuses. In this paper, an extension to traditional state estimation methods is proposed, which only requires a minor modification of existing WLS solvers based on gradient methods. Based on residual analysis, conditions are given in order to verify correct convergence at the end of a state estimation or to identify changes in connectivity due to opening/closing of control elements before proceeding to a new run. The method does not require including explicit binary variables to model the state of control elements, which would require complex heuristic-based solvers and would present scalability challenges for large networks with many such elements. Results on a real-world test case with two PRVs are reported to demonstrate the effectiveness and of the proposed method.

Peer-review under responsibility of the organizing committee of the XVIII International Conference on Water Distribution Systems

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doi:10.1016/j.proeng.2017.03.275

Keywords: State estimation; pressure control valve; water distribution systems.

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1. Introduction

State estimation is concerned with providing a complete representation of the internal condition or status of a system at a given instant of time and is applicable to virtually all areas of engineering and science [1]. In process monitoring and control, state estimation is a powerful tool to process collected measurements and to filter redundant and noise-corrupted ones in order to provide reliable estimates of state variables [2].

In the context of water distribution networks (WDNs), state estimation has been proposed as the core technology which can enable various applications ranging from real-time monitoring and control to anomaly diagnosis, such as leak detection and localization. The state estimation methods that have been reported for online monitoring of WDNs emphasize applications such as water demand estimation and forecasting [3, 4, 5]. These methods predict hydraulic behavior of the system based on prior estimation of demands and further correct the predictions using supervisory control and data acquisition (SCADA) measurements of variables such as flows and pressures. Use of state estimation for detection and localization of leaks was also widely studied, see for example [6, 7, 8].

The state estimation problem consists of using available measurements to reconstruct an estimate of the system hydraulics, i.e., nodal demands and flows throughout the WDN. The measurements are typically available from sparse telemetry sensors, such as flow at the inlet of a district metered area (DMA) or at some pipes and pressure at some nodes, or from utility estimates, for example prior estimates of the nodal demands. As detailed in [6], by appropriately choosing the state of the system as the set of nodal demands and flows at some links, an explicit relation between the measurements and the state can be found. The problem can then be efficiently solved, for example by minimizing the weighted least squares (WLS) difference between measurements and model predictions using gradient methods.

As pointed out by [8], WDS state estimation in the presence of control devices, such as pressure reducing valves, remains an open problem due to the complexity in modeling the discontinuities produced when the devices change status. In particular, measurements cannot typically be expressed as an explicit function of the system hydraulics, and accurately modeling the switching behavior would require the introduction of binary variables. As a consequence, the state estimation problem would increase in complexity often requiring complex heuristic methods with challenges in scalability for large networks with many control devices.

In this paper, a simple extension of existing state estimation solvers based on gradient methods, as introduced in [6], is proposed. The method allows to successfully deal with the presence of multiple control elements with minor impact on the computational complexity. Based on classical residual analysis, criteria for successful convergence of the state estimator are defined, such that correct estimation of the status of control elements can be verified. The same conditions allow to identify, eventually, a change in connectivity due to opening/closing of a control elements, so that a new state estimation run can be found. Depending on the number and the status of control elements, one to a number of simple state estimation runs is required to converge to the correct solution, thus keeping the computational cost reasonable even in the most complex cases.

Nomenclature

q	vector of nodal demands	$\mathbf{\Phi}(x)$	state-measurement mapping function
C	connectivity matrix	$\mathbf{\Psi}(\mathrm{x})$	hydraulic constraints
Q	vector of link flows	ε	measurement noise
ΔH	vector of head losses	W	weighting matrix
h	vector of nodal heads	$\mathbf{\Sigma}$	measurement error covariance matrix
h_F	vector of fixed heads	x	state vector
Λ	connectivity matrix of spanning tree	y	vector of observed hydraulic quantities
V	connectivity matrix of co-tree	z	measurement vector
$(\cdot)$	head loss equations in spanning tree	F	Jacobian matrix
$\Gamma_V(\cdot)$	head loss equations in co-tree		