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Comparative study of accuracy and computation time for optimal network reconfiguration techniques via simulation

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ABSTRACT

The objective of this work is to examine the effect of load flow analysis type, horizon length and discount factor, as well as switch ordering on the accuracy and speed of dynamic programming-based optimal network reconfiguration studies for minimizing loss. The author employs simulation of a 118-bus power system to obtain results. These results demonstrate that strong relationships exist between the parameters of an optimal network reconfiguration study and its performance. The author discusses how these relationships may be used to predict performance of future studies as well as, in turn, help power system operators make better decisions regarding parameterization and obtain maximum benefit from simulation-based analyses with minimum effort.

Introduction

General

Network reconfiguration via control of tie and sectionalizing switches plays an important role in power distribution system operation. Although such techniques are not commonly applied to transmission systems for reliability concerns, the need to do so will emerge with greater reliance on smart grid technologies and less-conservative operating schemes. This work looks to the future, studying network reconfiguration for loss minimization in transmission systems. Note that the generic term "switch" is used in reference to all transmission breakers, contactors, and relays that play a role in reconfiguration.

A traditional optimal power flow (OPF) study does not consider discrete control variables like switch status. It attempts to find the values of continuous system parameters (e.g. generator terminal voltage and real power injections) that minimize cost as defined by the user's objective function. Often, this function is formulated in terms of power loss (P_{Loss}) or voltage magnitude (V_{Min}, V_{Max}) and line flow (P_{Max}) limit violations. More recent papers describe how discrete variables like switch status may be incorporated into traditional OPF via techniques like dynamic programming [1–7]. In this paper, the term optimal network reconfiguration (ONR) study describes an optimal power flow (OPF) that defines optimal switch statuses only. The ONR is one type of OPF study.

Like any OPF, switching studies require significant computation time and effort when applied to large networks. As such, it is important to examine how the parameters of a study affect performance. The objective of this work is to examine the effect of load flow analysis type, horizon length and discount factor, as well as switch ordering on the accuracy and speed of dynamic programming-based optimal network reconfiguration studies for minimizing loss [8]. The author employs a Monte Carlo-Type simulation of variations on the IEEE Standard 118-bus power system for this purpose. The author's results, presented in Figs. 3–9, demonstrate that strong relationships exist between the parameters of an ONR study and its performance. He discusses how these relationships may be used to predict performance of future studies as well as, in turn, help power system operators make better decisions regarding parameterization and obtain maximum benefit from simulation-based analyses with minimum effort.

Literature survey/motivation

The majority of research works on the subject of network reconfiguration published in the past 25 years focus on power distribution and the analysis of radial systems [4,6,9–15]. This makes sense, given the greater availability of remote-controlled switches in distribution networks as compared to transmission and sub-transmission. However, with the emergence and adoption of smart grid technologies, it is increasingly important to consider both radial and looped networks in operating studies such as loss minimization. This work focuses on distribution systems over transmission and sub-transmission.

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One popular approach to research in the field of network reconfiguration is the application of emerging nonlinear system analysis techniques like simulated annealing [11,16]. These works are extremely interesting; obviously, they have significant potential to change the way operators measure and control power systems. However, the author presents very practical research in this paper, the results of which: (1) rely on techniques currently used in industry as well as (2) have potential to be used by independent system operators and utilities today.

A significant percentage of research works related to network reconfiguration utilize test systems with less than 35 buses and perform a limited number of trials [5,12,17]. This work takes a different approach, placing significant emphasis on generation of robust simulation results that employ fifty distinct 118-bus test systems.

The author is aware that application of dynamic programming and sensitivity analysis to power system problems is not a new approach. The method is commonly presented in power system analysis textbooks as a potential solution to unit commitment and economic dispatch analyses; additionally, a number of existing research works employ an application of dynamic programming to network reconfiguration like that presented in 'Formulation of ONR study' of this paper [18,19]. However, it is important to note that few of these works: (1) provide such in-depth simulation results and detailed description of optimal network reconfiguration performance, (2) explore the effect of analysis parameters like horizon length, (3) utilize more than fifty distinct 118-bus test systems, as well as (4) define a method for quantification of benefit as done here [14–18].

In this work, all variables and parameters are printed in italics. For example, a single state variable may be defined as *x*. All functions are printed in bold. For example, the state associated with an input u may be defined as $\mathbf{x}(u)$. All complex values are printed with arrow-hat. For example, the complex voltage at bus i may be defined as $\vec{V}_i$. All matrices are printed with an underline corresponding to its dimension. For example, a one-dimensional array of states that all are function of single input u may be defined as $\underline{\mathbf{x}}(u)$. A two-dimensional array of inputs may be defined as $\underline{\underline{u}}$.

Formulation of ONR study

The ONR problem is represented as the five-stage decision process. Each stage describes the status (open vs. closed) of a switch. The author developed a dynamic programming algorithm to analyze this decision process and solve for the optimal status of five network switches. This recursive algorithm is shown in (1)–(4), defined in terms of:

- *Finite Set of States* (s) – define the status of a given switch. For example, S_7 denotes that switch #3 is open.
- *Finite Set of Controls* (u) – define the desired status of one or more switches.
- *Finite Set of Transition Probability Functions* ($\mathbf{p}$) – defines the probability, for a given control (u_k), of transition between two states.
- *Finite Set of Immediate-Cost Functions* ($\mathbf{g}$) – define the cost associated with a transition between two states.
- *Finite Set of Future-Cost Functions* ($\mathbf{f}$) – define the cost associated with a future state in terms of all potential future control actions and state transitions.
- *Discount Factor* ($\mathbf{d}$) *and Horizon Length* (h) – define the effect of future states and transitions on immediate-cost.
- *Optimal Policy* ($\boldsymbol{\mu}$) – defines the optimal control action at state S_k, that which minimizes cost.

Eq. (1) provides the basis for the dynamic-programming algorithm used in this work. To determine the optimal policy (μ) at state $\mathbf{s}[k]$, the algorithm must calculate the sum of immediate and future costs for all potential control actions ($\underline{u}$). The optimal action, or policy, is that which yields minimum cost. Eq. (2) defines immediate-cost in terms of total real power loss within a power system. The loss function performs load flow analysis and calculates loss associated with a state $\mathbf{s}[k]$. Note that, although it is not shown in (2), this function requires knowledge of all switch statuses within the network. It is assumed to have access to this information. Eq. (4) defines discount factor ($\mathbf{d}$) as a function of horizon length (h) and takes on value of 0 or 1. Readers that desire further background on the application of dynamic programming to power system switching may refer to [20,21].

$$\boldsymbol{\mu}(\mathbf{s}[k],k) = \text{the value of } u \text{ such that min}\left\{\sum_{\text{for all potential } \mathbf{s}[k+1]} \overbrace{\mathbf{p}(\mathbf{s}[k],\mathbf{u}[k],\mathbf{s}[k+1])}^{\text{transition probability function}}\left[\overbrace{\mathbf{g}(\mathbf{s}[k],\mathbf{u}[k],\mathbf{s}[k+1])}^{\text{immediate cost function for control u [k]}} + \mathbf{d}[k]\overbrace{\mathbf{f}(\mathbf{s}[k+1],k+1)}^{\text{future cost function}}\right]\right\} \quad (1)$$

$$\mathbf{g}(\mathbf{s}[k],\mathbf{u}[k],\mathbf{s}[k+1]) = \overbrace{\mathbf{loss}(\mathbf{s}[k+1])}^{\text{total real power loss for network swith states described in } \mathbf{s}[k+1]} - \mathbf{loss}(\mathbf{s}[k]) \quad (2)$$

$$\mathbf{f}(\mathbf{s}[k],k) = \left\{\sum_{\text{for all potential } \mathbf{s}[k+1]} \begin{array}{l}\mathbf{p}(\mathbf{s}[k],\mathbf{u}[k],\mathbf{s}[k+1])[\mathbf{g}(\mathbf{s}[k],\mathbf{u}[k],\mathbf{s}[k+1]) \\ +\mathbf{d}[k]\mathbf{f}(\mathbf{s}[k+1],k+1)]\end{array}\right\} \quad (3)$$

$$\mathbf{d}[k] = \begin{cases} 0 & \text{if } k > h \\ 1 & \text{otherwise} \end{cases} \quad (4)$$

Problem statement and proposed solution

The optimal network reconfiguration (ONR) algorithm described in this work, because of its complexity, presents a number of potential implementations and endless potential for performance tuning. And, while it is advantageous in many respects, this only exacerbates the need to examine how study parameters affect solution accuracy and computation time.

The objective of this work is to examine the effect of load flow analysis type, horizon length and discount factor, as well as switch ordering on the accuracy and speed of dynamic programming-based optimal network reconfiguration studies for minimizing loss. For this purpose, a Monte Carlo-type simulation is employed in which repetitive ONR studies are performed and their results are analyzed. The author's results, presented in 'Simulation results', demonstrate that strong relationships exist between the parameters of an ONR study and its performance. These relationships may be used to predict performance of future studies as well as,