Sustainable Energy, Grids and Networks 8 (2016) 98–110

Contents lists available at ScienceDirect

Sustainable Energy, Grids and Networks

journal homepage: www.elsevier.com/locate/segan

Incorporating failures of System Protection Schemes into power system operation

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HIGHLIGHTS

- A generic dependability model for System Protection Schemes (SPS) is proposed.
- The model is embedded in a cost–benefit framework for optimal system operation.
- Significant cost savings are possible even with an unreliable SPS.
- Optimal operational strategies are closely linked to the failures modes of the SPS.

ARTICLE INFO

Article history:
Received 27 May 2016
Received in revised form
22 October 2016
Accepted 25 October 2016
Available online 29 October 2016

Keywords:
Corrective security
System protection schemes
Risk assessment
Cost–benefit analysis
Cyber–physical systems

ABSTRACT

The power transfer capability of existing transmission networks can be enhanced through the use of automated system protection schemes (SPS), which rapidly respond to disturbances on the network to keep the system's variables within operational bounds. However, reliance on such schemes may expose the network to large impacts – including blackouts – if the SPS does not respond as designed, so the deployment of SPS should balance risks and benefits. This paper formulates a risk-based cost–benefit framework that allows the operator to strike an optimal balance between constraint costs and risks of demand curtailment due to malfunctioning SPS. It is applied to a simple 4-bus power system inspired by the GB network, for which an exact optimisation problem can be formulated. A component-based dependability model is developed for the SPS to determine its failure modes and associated probabilities. The resulting cost-minimisation problem is solved for a range of operating conditions and SPS reliability levels. The results consistently show cost savings from the use of an SPS, even if it is highly unreliable, when a hedging strategy may be used. The optimal solution is highly sensitive to the problem parameters, but it is demonstrated that optimal operational strategies are associated with particular SPS outcomes. This finding may be used as empirical guidance to develop operational strategies for complex networks with unreliable SPS.

1. Introduction

System Protection Schemes (SPS), also known as System Integrity Protection Schemes (SIPS) or Remedial Action Schemes (RAS), are systems designed to detect abnormal power system conditions and initiate predetermined corrective actions to mitigate the impact of abnormal operating conditions, usually triggered by contingencies [1]. SPS interventions include changes in load, generation, or system topology, usually mediated by ICT infrastructure. These corrective systems help to protect the power system from high-impact low-probability events, including cascading failures [2].

The use of SPS is twofold: they can be used to increase the level of security—usually as part of last-resort defence plans, but they can also improve economic utilisation of electricity networks, alleviating operational security constraints. In this second application, they provide *corrective security*, which should be contrasted to the traditional preventive approach in which security is guaranteed through redundant transmission infrastructure [3]. Operationally, a preventive security approach results in high operational costs, especially when large amounts of remote renewable resources are connected to the grid: the pre-fault security constraints may require costly curtailments of renewables and dispatching generators out of merit [4]. In the planning time frame, this paradigm provides an incentive to invest in costly transmission reinforcements [5].

For these reasons, there has been growing interest in exploring and expanding the application of SPS to release extra capacity to

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http://dx.doi.org/10.1016/j.segan.2016.10.002

network users [4,6], illustrated by deployments in e.g. Canada, Brazil and Chile. Indeed, a recent survey by IEEE and PSERC [7] on global experiences with SPS shows an increase in the use of such schemes. However, SPS actions are not infallible in practice, and relying on them means exposing the system to additional risks resulting from SPS malfunction. If such failures occur, they may drive the system far outside its regular operating regime, potentially triggering harmful blackouts. Therefore, the increasing use of these schemes needs to be accompanied by a better understanding of their true impact, as undesirable SPS operations may result in a deterioration of the overall system reliability.

SPS malfunctions are not as infrequent as one may think. Panteli et al. [8] reviewed NERC System Disturbance Reports from 1986 to 2009 and found that of 26 SPS malfunctions, 11 cases were related to ICT operational failures. SPS malfunctions have also played a role in Europe, as happened in the Nordic network in 2005 [1]. Moreover, in a 1996 IEEE-CIGRE survey [9], respondents from the power industry assigned very high cost estimates to SPS failures. This underscores the necessity of a robust decision framework for SPS operation that takes into account SPS failure modes and their likelihood of occurrence. SPS failures are classified into dependability-based (failure to operate when required) and security-based (accidental activations). Dependability failures typically receive the most attention in protection system design and system studies, because failure of a protection system to operate when the system is in a state that requires it, is likely to have significant consequences [10].

Despite the potential risks from SPS malfunctions, the operational rules for these systems have historically been determined based on deterministic techniques combined with expert judgement [1]. In recent years, probabilistic analysis has increasingly been used to address uncertainties in pre-fault operating conditions (e.g. demand levels, outages, variable generation, etc.). Hydro-Quebec [11,12] has performed simulations based on historical snapshots and made use of techniques such as data mining and combinatorial optimisation to optimise the settings of generation and load shedding protection systems [11,12]. Similarly, Hsiao et al. [13], and Wen-Ta and Chao-Rong [14] perform simulations under different operating conditions to optimise SPS settings in the Taiwan power system. Another example is BC Hydro [1] which has implemented an arming scheme for multiple SPS such as generation intertripping using off-line Monte Carlo simulations. All these efforts have resulted in robust rules for SPS operation based on a sensible coverage of operating conditions and contingencies, but dependable SPS operation has commonly been assumed for these studies.

Integrating the risks caused by unreliable SPS into power system operations is a challenging task, due to the large number of possible scenarios and the difficulty involved in modelling the consequences of SPS malfunctions. A generic risk assessment for SPS based on FMEA and Markov modelling is presented in Fu et al. [15], where the authors focus on computing the optimal arming point of a generation rejection scheme. Panteli and Crossley [16] also calculate optimal arming points that balance the risks stemming from a lack of dependability and accidental activations. These works are concerned with risk-based optimal configuration of SPS. However, the computation of impacts from SPS malfunction scenarios has commonly not included the response of the power system in complex post-fault scenarios. The latter is often highly nonlinear, for example when the malfunction triggers a cascading outage. Besides, the risks from unreliable SPS operation should be embedded in a system-level cost–benefit analysis, so that it is accounted for in operational decisions regarding dispatch and the loading of transmission lines. Ultimately, such a framework seeks to balance benefits and risks associated with different levels of network utilisation and investment, as in the case of probabilistic security standards [17]. Moreno et al. [4] have presented an initial investigation of this topic, but their analysis included only a very simple model of SPS malfunction and its impacts.

SPS use long-range communication and automated decisions to improve the control of the physical electricity grid. As such, they form an excellent model system to study the complexities involved in the modelling and operation of cyber–physical energy and communication systems. The development of reliability analysis methods for such systems is an open research challenge [18].

This paper makes a number of contributions towards the risk-aware operation of power systems using unreliable SPS:

- We formally state the decision problem faced by the operator to simultaneously optimise the dispatch of generators and the arming of the unreliable SPS, introducing the different cost components of the objective function (Section 2).
- A simple four-bus model system is introduced to demonstrate the salient properties of this optimisation challenge. The model is sufficiently simple to allow a closed form expression for the optimisation (Section 3 (model) and Section 4 (optimisation)).
- The model makes use of a high-level SPS dependability model, based on generic components (relay, communication channel, logic controller, breaker), the results of which are summarised by a conditional probability table for the SPS response (Section 4).
- Section 5.1 investigates the properties of the optimal dispatch and SPS configuration, across a range of operating conditions and SPS reliability scenarios. The results demonstrate the robust ability of even an unreliable SPS to contribute to a reduction in system costs, often through hedging against (partial) failures.
- We demonstrate that the optimal SPS configuration, for any dispatch, is a member of a discrete set of *candidate solutions*, which are associated with specific SPS outcome (including its failure modes). This finding is likely to be beneficial for the development of efficient optimisation methods for large power systems.

It should be noted that the framework presented in Section 2 is widely applicable, but implementing such a framework for large networks that may suffer complex cascading outages is far from trivial. The implementation in Sections 3 and 4 stops short of that long term aim by focusing on a simple network configuration. The transparency of this model enables an in-depth understanding of the properties of the solutions (Section 5). Such understanding will contribute to the future development of generalised methods that can be applied to complex power systems.

2. Problem statement

We consider the problem of optimal system operation from the perspective of a single central operator in a congested network with pre-contingency security constraints. In the operational time frame, the operator must decide on the optimal dispatch of generators to minimise operational costs. In addition, it can configure and arm an SPS to relax security constraints. Efficient operation of the system is achieved by co-optimising the dispatch and SPS configuration in a way that balances the benefits from the utilisation of low-cost generation (e.g. wind) and the risks due to contingencies and unreliable SPS operation.

Fig. 1 illustrates the operational decision problem. We assume that the operator has no recourse after a contingency occurs, so that the dispatch and SPS configuration fully define the system's response to faults. We further assume that contingencies unrelated to the SPS are neutralised by a security constrained OPF as part of the dispatch so that only SPS-related contingencies need to be considered.