SAND2021-5019C

Power System Protection Parameter Sensitivity Analysis with Integrated Inverter Based Resources

Adam K. Summers, Ronald C. Matthews, Trupal Patel, and Matthew J. Reno

Sandia National Laboratories, Albuquerque, New Mexico, 87123, United States

***Abstract*—As conventional generation sources continue to be replaced with inverter-based resources. The traditional protection schemes used at the distribution level will no longer be valid. Adaptive protection will provide the ability to update the protection scheme in near real-time to ensure reliability and increase the resilience of the grid. However, knowing and detecting when to update protection parameters that are calculated with an adaptive protection algorithm to prevent unnecessarily communicating with relays still needs to be understood. The proposed method will provide a sensitivity analysis to understand when it is necessary to issue new parameters to the relays. The results show that rather than issuing new settings at every adaptive protection algorithm time step, by using the proposed sensitivity analysis, only the imperative protection parameters are communicated to the relay, which improves the optimal use of the communications resources.**

Keywords—power system protection, inverter-based resources, adaptive protection, sensitivity analysis, Karush-Kuhn-Tucker, fault analysis.

I. INTRODUCTION

The modernization of the electric grid continues to accelerate away from the use of fossil fuels and large synchronous machines towards solar, wind, and storage inverter-based resources (IBRs). This new grid will have the advantage to incorporate the IBRs in a distributed manner. Counter to the past, with centrally located generation, long transmission lines, and terminating with a distribution system. The paradigm shift in the generation and distribution of energy has created a host of power system opportunities [1]. New grid code requirements in Hawaii and California and the national level are being developed and deployed [2] to take advantage of the IBRs unique system locations and controls. Furthermore, unique system designs, such as microgrids, can be utilized to provide resilience to the grid during stressed events [3].

The increasing penetrations of IBRs on the distribution system are creating reverse power flows, which impacts the protective devices and fault location techniques [4, 5, 6]. A potential solution is adaptive protection that uses a relays ability to store multiple groups of protection settings, but this is limited by the number of setting groups that a relay can store internally, such as, the SEL-751. A solution to the limited number of group settings a relay can store is using centralized adaptive protection with communication to the relays. This typically involves the relays using SCADA to send their local current and voltage measurements back to a centralized location where an adaptive protection algorithm would use those measurements to calculate new protection parameters and then send the updated parameters back to the relays. However, the previously described architecture can be problematic for several reasons. A common issue with adaptive protection is determining how often to update the settings or what events could initialize new parameters being sent. In [7] the protection parameters could be updated at regular time intervals. In [8], the authors update after a system reconfiguration.

Here in we propose a sensitivity analysis to be used in conjunction with previous work in [7]. With communication enabled adaptive protection schemes, it will become imperative to know if new protective settings are needed to be deployed to the relays

This article is organized as follows. Section II focuses on the introduction of the experimental setup. Section III describes background and sensitivity analysis. Section IV deals with the proposed method. Section V focuses on preliminary results.

II. EXPERIMENTAL SYSTEM

The test system is a modified version of the IEEE 13 bus system and is shown in Fig 1. The system models a small distribution feeder operating at 4.16 kV. The system is connected to the grid through a 115 kV to 4.16 kV substation transformer at bus 650. A voltage regulator is connected between bus 650 and 632. The system contains unbalanced overhead and underground lines and unbalanced loads, the total system load is approximately 3.15+1.58j MVA. The IEEE 13 bus system was modified by adding PVs and directional overcurrent relays to the system. Four photovoltaics (PV) systems rated at 1.5MW, 1.0 MW, 800 kW, and 800 kW are connected to buses 650, 633, 675, and 680 respectively. The PV systems are current-limited to 2 pu. The system is modeled in OpenDSS, which is used to perform the fault analysis required to generate and test directional overcurrent relay settings.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

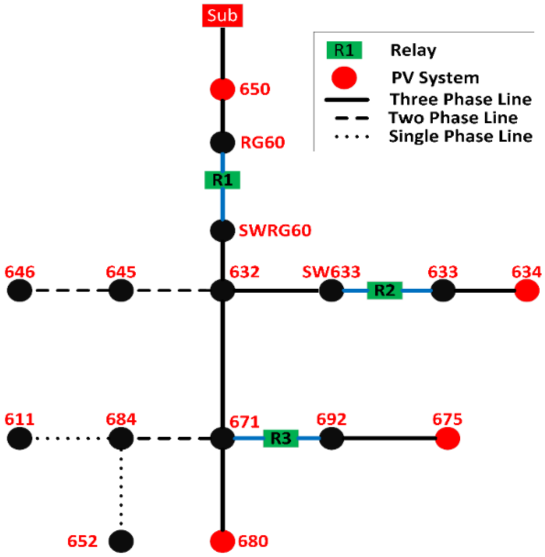

Figure 1 Modified IEEE 13 Bus System

III. Background: KKT and Sensitivity Analysis

In general, sensitivity analysis can be used to determine whether changes in parameters or control variables of an optimization problem will push the solution to an optimization problem either into an infeasible region or into a suboptimal region. This problem can become quite complex when control variables are considered, especially for a nonlinear constraint problem.

The optimal relay coordination problem is a mixed-integer nonlinear programming problem (MINLP). However, let us momentarily consider the simple Linear Programming problem (LPP).

$$\text{Minimize } Z = \mathbf{cx}, \tag{1}$$

s.t.

$$\mathbf{Ax} \leq \mathbf{b} \tag{2}$$

$$\mathbf{x} \geq \mathbf{0} \tag{3}$$

According to [9], sensitivity analysis for the LPP can be classified as one of three types:

1) Changes in b_i
2) Changes in coefficients a_{ij}
3) Introduction of a new variable

Note that in [9], the 2nd classification is divided into (i) changes in a basic variable and (i) changes in a nonbasic variable. However, for the purposes of this paper, the broader classification is sufficient.

Similarly, for the MINLP,

$$\text{Minimize } Z = f(\mathbf{x}), \tag{4}$$

s.t.

$$\mathbf{g}(\mathbf{x}) \leq \mathbf{b} \tag{5}$$

$$\mathbf{x_d} \in \mathbf{r} \tag{6}$$

$$\mathbf{x_d} \subseteq \mathbf{x} \tag{7}$$

where, $\mathbf{g}(\mathbf{x}) \in \mathbb{R}^{\mathbf{m}}$ is the vector of nonlinear constraints, $\mathbf{x} \in \mathbb{R}^{\mathbf{n}}$ is the vector of decision variable, $\mathbf{x_d} \in \mathbb{R}^{\mathrm{p}}$ is the vector of discrete decision variables, and $\mathbf{r} \in \mathbb{R}^{\mathbf{p}}$ is a vector of integer constraint sets. Similar to the LPP case, only (5) needs to be validated to establish feasibility.

For the relay coordination problem, we seek to determine when a substantial event has occurred. That is, we seek to determine when the change in PV output or loading becomes sufficiently large that the prior result is no longer feasible.

The above sensitivity analysis classifications can be rewritten for the general continuous nonlinear programming problem (exclude constraints (6) and (7)) as

1) Changes in b_i
2) Changes in the function $g_i(\mathbf{x})$ (the function itself, not $\mathbf{x}$)
3) Introduction of a new variable

Then the currents are updated, the multiples of pickup will change, thus changing the constraint function $\mathrm{g}(x)$. Otherwise, the problem will remain unaltered. Therefore, only the 2rd classification is of interest. Neglect (6) and (7) momentarily and consider the general continuous nonlinear constrained problem. Karush-Kuhn-Tucker (KKT) conditions define the necessary conditions for optimality. That is, a solution can be optimal if and only if there exists a set of values u_1,..,u_m such that

$$\frac{\partial f}{\partial x_j} - \sum_{i=1}^{m} u_i \frac{\partial g_i}{\partial x_j} \leq 0 \textbf{ OR } x_j^* \left(\frac{\partial f}{\partial x_j} - \sum_{i=1}^{m} u_i \frac{\partial g_i}{\partial x_j} \right) = 0 \tag{8}$$

$$g_{\boldsymbol{i}}(\mathbf{x}^*) - b_i \leq 0 \textbf{ OR } \boldsymbol{u_i}[g_i(\mathbf{x}^*) - b_i] = 0 \tag{9}$$

$$x_j^* \geq 0 \tag{10}$$

$$u_i \geq 0 \tag{11}$$

for $i = 1,\ldots,m$ and $j = 1,\ldots,m$. The * denotes the optimal solution. Note that the elements of the vector $\mathbf{g}$ are present in both (8) and (9). Therefore, if the solution in (9) is satisfied, the solution can be an optimal solution. This only says that the solution can be optimal, not that it is. The sufficient condition for optimality is as follows. If $f(\mathbf{x})$ is concave and all elements of $\mathbf{g}(\mathbf{x})$ are convex, the solution is an optimal solution. Note that KKT uses curvature and derivatives to locate locally optimal solutions.

When constraints (6) are considered (7), the KKT conditions no longer hold because derivatives are no longer valid. Therefore, no statement can be made about whether the current solution is locally optimal. For relay coordination problem posed in this paper, all of the variables are discrete. Therefore, KKT conditions will not apply and statements about optimality cannot be made about local optimality based upon these conditions.

The focus in this paper will be solely on maintaining feasibility after a current-induced change in $\mathbf{g}$. If the solution remains feasible, keep it. Otherwise, recalculate. This is sufficient for protection because the only case where a solution would be considered "bad" is if the CTI is violated or if the damage curves for substation transformers are violated. These specifically define the optimization constraints of the problem. Therefore, any feasible solution will be acceptable from a protection standpoint.

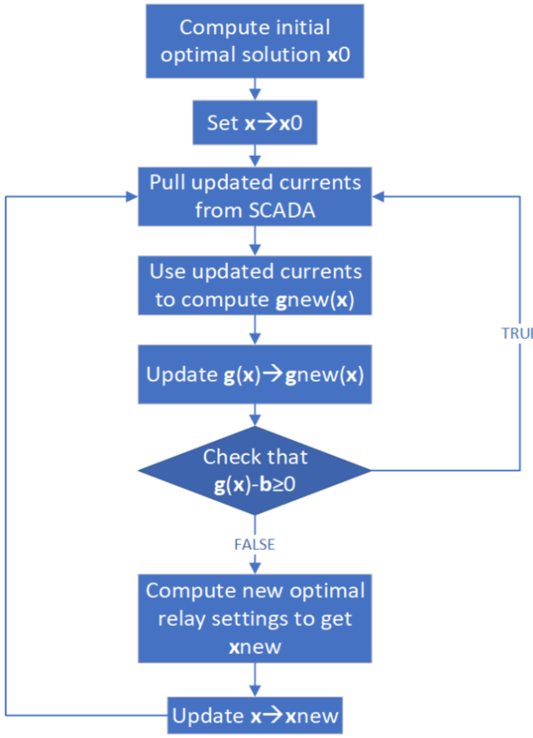

Figure 2 Event-Driven Sensitivity

IV. Proposed Method

To avoid unnecessary computations, especially for larger systems, an event-driven optimization update process is proposed. The update is triggered when the prior solution becomes invalid due to system-wide changes in the current related to load and PV fluctuations. The process is summarized in Fig 2. Keeping the notation of (4)-(7), $\mathbf{x}_0$ is this initial solution to the problem at the initial system state. Let n_r be then number of relays. Forward and reverse setting are treated as separate relays. $\mathbf{x}^{\mathbf{T}} = [\mathbf{TDS}^{\mathbf{T}}, \mathbf{Type}^{\mathbf{T}}]$, where **TDS** is the $n_r \times 1$ vector of time dial settings and **Type** is the $n_r \times 1$ vector of relay characteristics. Both **TDS** and **Type** are vectors whose elements come from discrete, finite sets. These variables will be defined in greater detail later. **g** defines the coordination constraints.

V. Preliminary Results

As seen in Fig 3, results over a two-day time period with a five-minute time step are plotted. The vertical dash red lines indicate when new directional overcurrent settings will be communicated to the relays. As expected during periods without PV production (nighttime) there are few updates to the relays. The settings are recalculated when the load and PV generation are near equal. Which occurs in the morning and late afternoon. The first day a total of 11 different relay parameter updates. The second day requires 14 different relay parameters to be communicated. The full manuscript will include a yearlong sensitivity analysis of the test system under varying load and PV profiles.

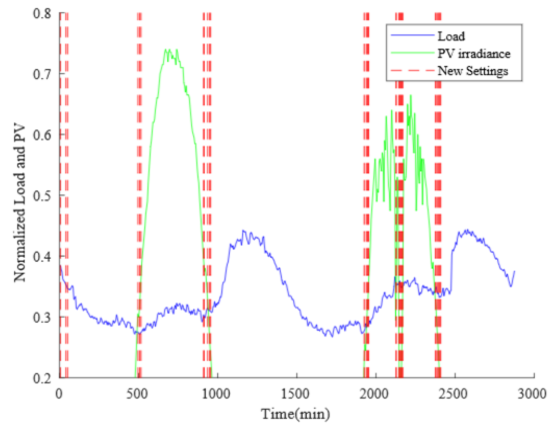

Figure 3 Two Day Sensitivity Analysis

Acknowledgment

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number 36533. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC. a wholly owned subsidiary of Honeywell International, Inc., for the U.S Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

VI. References

[1] B. Kroposki, B. Johnson, Y. Zhang, V. Gevorgian, P. Denholm, B.-M. Hodge and B. Hannegan, "Achieving a 100% Renewable Grid: Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy," *IEEE Power & Energy Magazine,* pp. 61-73, March/April 2017.

[2] *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces (IEEE Std 1547-2018),* Piscataway: IEEE, 2018.

[3] M. Higginson, K. Moses, B. Harwig, P. Curtiss and H. Tiwari, "Microgrid Seamless Transitions Between Grid-Tied and Islanded Operation: A Case Study," in *2020 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, Chicago, 2020.

[4] J. Blair, G. Hataway and T. Mattson, "Solutions to Common Distribution Protection Challenges," in *2018 IEEE Rural Electric Power Conference (REPC)*, Memphis, 2018.

[5] B. Palmintier, R. Broderick, B. Mather, M. Coddington, K. Baker, F. Ding, M. Reno, M. Lave and A. Bharatkumar, "Emerging Issues and Challenges in Integrating Solar with the Distribution System," Office of Energy Efficiency & Renewable Energy, Washington D.C., 2016.

[6] G. J. Brice, M. S. S. Venkata, P. Kuntz, S. Milovanovic, E. Sortomme, J. Ren, S. Adhikari and J. Gantz, "Integrated Smart Distribution RD&D Project Final Technical Report," U.S. Department of Energy Office of Scientific and Technical Information, Washington D.C., 2017.

[7] R. Matthews, T. Patel, A. Summers, M. Reno and S. Hossain-McKenzie, "Per-Phase and 3-Phase Optimal Coordination of Directional Overcurrent Relays Using Genetic Algorithm," *MDPI Energies,* 18 March 2021.

[8] K. Sedghisigarchi and K. T. Sardari, "An adaptive protection strategy for reliable operation of microgrids," in *IEEE International Energy Conference (ENERGYCON)*, Riga, 2018.

[9] F. S. Hillier and G. J. Lieberman, Introduction to Operations Research, New York: McGraw-Hill, 2005.