# Is the Smart Grid A Good Investment?

Ahmet Onen
Electric and Electronics Engineering
Abdullah Gul University
Kayseri, Turkey
ahmet.onen@agu.edu.tr

Robert Broadwater
Electric and Computer Engineering
Virginia Tech
Blacksburg, Virginia, USA
dew@edd-us.com

***Abstract*— Electric distribution design and operational goals include meeting customer reliability requirements at the lowest cost. Smart Grid investments have the potential for helping meet these goals, and this paper presents a series of analyses that evaluate the incremental economic benefits of smart grid automation investments. Smart Grid investments provide a number of benefits to customers. Here only benefits that can be objectively quantified in terms of economic savings are considered. Smart Grid automation investments in this work include investments in feeder efficiency, automated switches, and coordinated control of capacitor banks, voltage regulators and load tab changers. Benefits that come from these investments are improved efficiency, reduced demand, shortened storm restoration time, and improved performance during reconfiguration events. The analyses used in the evaluation are very detailed, involving hourly, quasi-steady state power flow analysis over a ten year period for calculating energy consumption and costs, and Monte Carlo simulations for six different storm types. The evaluation shows that similar to other industries, an investment in automation can be justified in terms of hard dollars.**

***Index Terms*-- Smart Grid automation investments, Quasi-steady state power flow, Monte Carlo simulation of storms, Locational Marginal Price (LMP), Phase Balancing, and Capacitor Design.**

## I. INTRODUCTION

Smart grid automation investments that result in making better use of existing distribution system capacity and which affect the distribution system reliability, capacity, and efficiency are of interest. In the work here evaluation of smart grid investments are based on hard dollars. The term hard dollar is used to mean that the economic benefits can be quantified in terms of dollars when costs of alternative designs are compared. This stands in contrast to soft dollar benefits which, for example, attempt to estimate a value to customers of reduced outages, but which rely upon economic values that are difficult to quantify. However in hard dollar calculations, costs/savings are reflected in utility and customer financial statements.

Operating and equipment installation costs are among the chief economic concerns for utility companies. Utilities look for ways to update their systems to meet load and reliability requirements at the lowest cost, but updating an entire system all at once may not be cost effective or feasible. Thus, utilities typically update their system in stages. In addition to the hard dollar benefits investigated here, utilities also have the following motivations for system upgrades: reduced losses are good for the environment; maintaining customer voltage profiles within standards requirement; reduced storm restoration time; remote monitoring of the system that provides more understanding which will lead to better decisions.

There is little work that has been presented in the areas of preparing a smart grid simulation model that uses controllable devices to reduce system losses and increase system capacity, assessing reliability improvements from automated switches, and quantifying the economic benefits of these investments. Reference [1] proposes a phase balancing algorithm without considering economic evaluation. Similarly [2] proposes a method to optimum capacitor placement without considering cost of losses. References [3-4] propose coordinated control that can be hourly controlled and updated local controller settings based on hourly load changes. References [5-7] investigate the benefits of distribution automation on system reliability without considering economics of reliability.

Hard dollar benefits from smart grid automation investments considered here arise from investing in automated switches and model-centric coordinated control of automated reconfiguration, voltage regulators, and capacitor banks. Hard dollar benefits from three types of studies are considered. The first two studies considered, prior to the smart grid investment studies, but important to the success of the smart grid investments, are phase balancing and capacitor placement. These studies are viewed as necessary to ready the distribution system for smart grid devices, such as automated switches, model-centric coordinated control, and even solar generation. These studies help to improve the efficiency and also help to make full use of the existing capacity by balancing the loading across the phases and by improving the power factor.

The second type of study addressing hard dollar savings is storm response. Over a ten year period the system under study experienced 89 storms, with more recent storms impacting the utility with costs in the neighborhood of $25 to $35 million dollars [8]. During a storm event the hourly costs of crews are very high. If switch automation can be used to allow crews to spend less time operating switches, then repairs can be completed quicker, reducing both the cost of repair and the customer downtime. Six different types of storms are considered [9], and Monte Carlo simulations that consider up to 3000 individual simulations for each type of storm are performed, where storm responses are compared with and without automated switches. In performing the cost evaluations of the storm restorations, the storm response simulation uses a reconfiguration algorithm [10].

The third type of study considered here evaluates the reduction of feeder losses and load energy from implementing model-based, coordinated control of voltage. Here voltage regulators and load tab changers are used to implement Conservation Voltage Reduction, while switched capacitor banks are used to flatten the voltage profile across the feeder [11].

Cost reduction benefits derive from delaying larger investments in new substations (that is, more fully utilizing the capacity of the existing system to maintain reliability), sending crews home earlier from storm operations, reduction in load energy, and a reduction in feeder losses. Another benefit that derives from coordinated control is the improved performance obtained during reconfiguration events where on average customer power is restored quicker.

All studies are performed using an hourly load curve [12], and some studies, using load growth factors, analyze the system for a ten year period on an hourly basis. Electric energy prices are also estimated for the ten year period. Here the Locational Marginal Price (LMP) data is escalated based upon the DOE forecast for gas energy prices. Thus, the assumption is made that the electric energy prices will escalate as the gas energy prices do. Hence, time varying load is modeled along with the time varying cost of electricity. Monte Carlo storm simulations presented use statistical data derived from historical storms, and, for a specific type of storm, simulate up to 3000 storms to derive the statistics presented.

This paper is organized as follows: Methodologies used in the studies are described in section II. Results of the studies are presented in section III. Finally, conclusions are presented.

## II. PROCEDURE FOR HARD DOLLAR CALCULATIONS

### A. *Phase Balancing Calculation*

Phase balancing and capacitor placement are considered here as preparatory to the smart grid investments. That is, by making the investments in phase balancing and improved voltage control, the model-centric coordinated control is able to perform its functions better. In other words, we get more from the smart grid investments by making these preparatory investments.

Utilities generally have many single phase lines going to customers, which result in greater losses in all conductors from the substation to the customers, and the losses are proportional to the square of current. Phase balancing involves moving a lateral from one phase to another [1]. When feeders are imbalanced, phase balancing is often the most cost-effective way to reduce feeder losses, so it is considered before other efficiency upgrades. Also, phase balancing can affect the results of other designs, such as the capacitor design to be considered in the next section. The only cost is the crew's time and the short interruption caused by moving phases.

The phase balancing algorithm used prioritizes the phase moves, with the highest priority phase move providing the greatest reduction in losses, the next highest priority phase move providing the next greatest reduction in losses, and so forth. The phase balancing algorithm also determines a balance that minimizes the losses over a set of time points, such as summer and winter peak, average, and minimum loads.

### B. *Capacitor Placement and Coordinated Control Calculation*

Capacitors also help to reduce system losses [13]. Since the feeders studies here already had many existing capacitor banks, the study here may be thought of as a capacitor replacement study. Typically, the cost associated with capacitors is much higher than phase balancing, but still it is often worthwhile for utilities to install capacitors to correct the power factor and maintain the voltage level [2]. Generally, phase balancing should be performed before capacitor placement, since the phase balancing result often will affect the capacitor placement [14].

Coordinated control of capacitors and voltage regulators can improve feeder capacity and efficiency, especially when that control is model-centric rather than based on local measurements [11]. That is, a control scheme running on a central server considers many types of measurements throughout the system and can perform simulations (even forecast simulations in addition to simulations based on the present state of the system) to determine the optimal operation and coordination of devices. Smart grid communications can provide this capability, and is similar to control in other types of coordinated control applications, such as found in some central generation plants. If communications are lost, then control becomes entirely feedback based only on local measurements.

Thus, the coordinated controller can make better decisions than a local controller that may be operating based on only one or two local measurements and limited knowledge of the rest of the system. Good coordinated control of capacitors involves two primary objectives: improving system efficiency and preventing under- or over-voltage [14]. Secondary benefits of coordinated, model-centric, control include reducing capacitor switching (to reduce the likelihood of capacitor failure) and providing remote monitoring so that the utility knows when the capacitor has failed. Another cost-savings value of coordinated control includes savings by not having to send crews out to the various capacitor locations to either inspect or switch them manually.

If the utility relies upon local control only, it is difficult, if not impossible with some renewable generation cases, to find set points that provide the needed voltage support from peak load to light load. In addition to controlling capacitors, voltage regulators and load tab changers are included in the coordinated control. With model-based, coordinated control, driven by numerous measurements throughout the system, the utility does not need to worry about setting the voltage too high off-peak and can gain maximum voltage regulation on-peak.

Another benefit of using the coordinated control scheme to control voltage regulators and load tap changers is that the utility gains the ability to perform Conservation Voltage Reduction (CVR) [16]. And if capacitor banks are used to flatten the voltage profile across the feeder, then maximum benefits can be obtained from the CVR. That is, by regulating the voltage to the lowest level acceptable to customers, the overall energy drawn by voltage-sensitive loads is reduced. Reducing these loads provides utilities with the benefit of reducing loading at peak (and thereby delaying capital equipment upgrades) and provides many customers with the benefit lower energy costs. However, a major benefit of the model-based, coordinated control is the ability to switch control objectives. That is, the coordinated control can be used to achieve minimum losses on the distribution system or it can be used to achieve maximum capacity under heavily loaded conditions [11]. Here the coordinated control solution for two objectives, minimum distribution system losses (Efficiency Mode) and CVR, will be compared.

### C. *Storm Restoration Calculation*

Economic benefits are available from automated switches during storm restoration. This is an investment that leads to reduced field crew expenses, which can amount to a million dollars for a single hour cut off of a storm response [9]. The cost savings comes from less crew time operating switches. In restoring power the labor is generally the major cost. During severe storms, utilities often hire crews from neighboring utilities at a premium [15]. The operational time savings from automated switches can be calculated as "hard dollar" benefits, and can motivate smart grid investments even without including the "soft dollar" benefits associated with improved reliability. Table I provides descriptions of different storm types which are used in the study here.

TABLE I
STORM CLASSIFICATION

| Storm Type | Description | T Range ( °F ) | Wind Speed (mph) |
|---|---|---|---|
| **H** | High temperature, no strong wind | MaxT > 80 | WS <= 20 |
| **HS** | High temperature, strong wind | MaxT > 80 | WS > 20 |
| **L** | Low temperature, no strong wind | MinT < 32 | WS <= 20 |
| **LS** | Low temperature, strong wind | MinT < 32 | WS > 20 |
| **M** | Moderate temperature, no strong wind | MaxT <= 80<br>MinT >= 32 | WS <= 20 |
| **MS** | Moderate temperature ,strong wind | MaxT <= 80<br>MinT >= 32 | WS > 20 |

**MaxT:** maximum temperature; **MinT**: minimum temperature; **WS:** wind speed

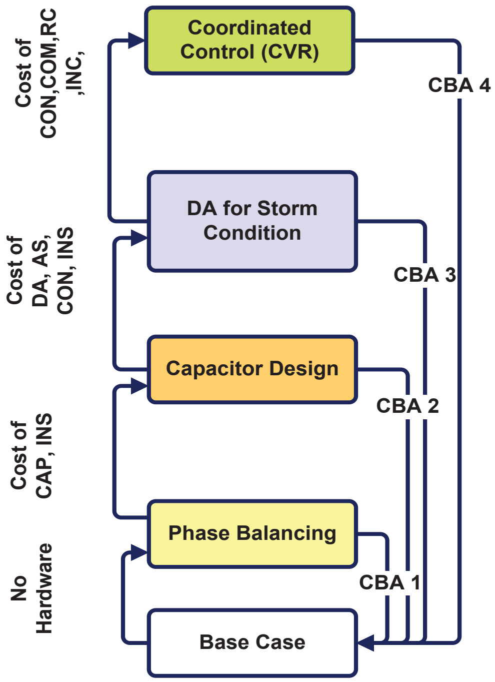
### D. *Evaluating Incremental Economic Benefits*

The selected smart grid investments are illustrated in the flow chart shown in Figure 1. First phase balancing is performed, which as discussed earlier, leverages the later investments in smart grid. Phase balancing is considered before capacitor placement because it affects loading and voltages, and thus affects the locations at which capacitors need to be placed. Phase balancing increases the utilization of the capacity across the three phases, which results in more capacity for reconfiguration operations.

Next, automated switches are modeled, which provide rapid access to existing system capacity. The distribution automation hard dollar savings comes from delaying investments in new system capacity and also reduced field crew hours, especially during major storms.

Two types of economic benefits derive from coordinated control which are reduced system losses and reduced load energy due to CVR.

Hard dollar savings from each investment are referenced to the system that resulted from the previous investment. That is, the incremental benefit of each investment is considered. Thus, savings resulting from the investment in capacitors is determined by comparing the cost of operating the system with the new capacitor design to the cost of operating the phase balanced system. Likewise, the cost of operating the system with the automated switches is compared to the cost of operating the system with the new capacitor design, and so forth.



**DA : Distribution Automation**
**AS: Automated Switches**
**RC: Remote Control**
**CON: Controller**
**COM: Communication**
**INS: Installation**
**CAP: Capacitores**

Fig. 1. Smart Grid Economic Analysis Flow Chart

## III. CASE STUDIES

Figure 2 shows the system used for the study. Table II presents hard dollar benefits calculated for the investment stages. The investment cost, hard dollar savings, and dollars saved per dollar invested associated with the investment stages illustrated in Figure 1 are shown in Table III.

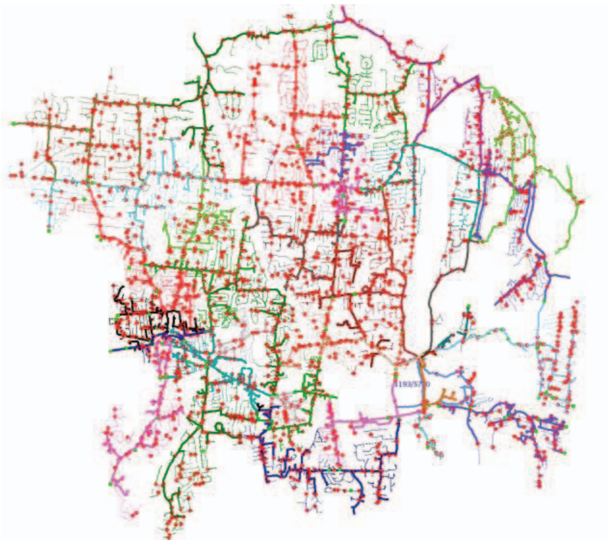


Fig. 2. System Evaluated for Hard Dollar Investments

TABLE II
10 YEARS SUMMARY OF CASE SAVINGS

| Case | Saving ($k) |
|---|---|
| *CBA1: Phase Balancing* | 464 |
| *CBA2: Capacitor Design* | 1,756 |
| *CBA3: Storm Restoration* | 9,592 |
| *CBA4: Loss Reduction* | 89 |
| *CBA4: Energy Reduction* | 3,797 |

From the phase balancing and capacitor design efforts a benefit of 2,220 $k in loss savings is realized savings. The largest benefit accrues from the storm restoration. But should be noted that this benefit is based upon extrapolating the results from the pilot system studies to the entire power system, which consists of 100's of feeders.

TABLE III
INCREMENTAL BENEFIT RATIO

| Case | Investment Cost ($k) | Savings ($k) for 10 years | $ Saved/ $ investment |
|---|---|---|---|
| *CBA1: Phase Balancing* | 56 | 464 | 8.29 |
| *CBA2: Capacitor Design* | 496 | 1,756 | 3.54 |
| *CBA3: Storm Restoration* | 1,953 | 9,592 | 4.91 |
| *CBA4: Coordinated Control* | 68 | 3,866 | 56.85 |

Table III shows the investment cost and saved/investment ratio for each of the cases. Investor can look into this Table III and decide where they can make an investment.

## IV. CONCLUSION

This paper summarizes results for a series of hard dollar smart grid investment evaluations. Details of the simulations performed, including the Monte Carlo storm simulations and reconfiguration for restoration evaluations, are referenced. The first two case studies presented address preparing the existing system for smart grid investments. The third case study addresses how automated switches can be used to reduce field crew expenses. Case study four evaluates the benefits of model-centric control for simultaneously reducing system losses and load energy. The smart grid investment strategy presented here shows promising hard dollar benefits.

## REFERENCES

[1] Lingyun Wang, Ahmet Onen, Jeremy Woyak, Reza Arghandeh, Robert Broadwater, "Electric Power Distribution Feeder Performance Evaluation and Distributed Computation," El-Cezerî Journal of Science and Engineering, January 2015, Vol. 2, No. 1, pp. 59-67.

[2] Osama M. Aloquili, Nazih M. Abu-Shikhah, "Power Factor correction capacitors for utilizing power consumption in industrial plants", International Journal of Energy Technology and Policy 2010 - Vol. 7, No.3 pp. 288 - 308.

[3] A.Onen, D.Cheng, R. Arghandeh, J. Jung, J. Woyak, M. Dilek, R. Broadwater, "Smart Model-based coordinated control based on feeder losses, energy consumption, and voltage violations," Electric power system component and system, vol. 41, issue 16, pages 1686-1696, August, 2013.

[4] J.Jung, A.Onen, R. Arghandeh, R. Broadwater, "Coordinated Control of Automated Devices and Photovoltaic Generators for Voltage Rise Mitigation in Power Distribution Circuits", Renewable Energy 66C, pp 532-540, January 2014.

[5] K.Alekhya, P.S.R. Murthy and C. Bhargava " Assessment of Reliability for Distribution feeders on the bases of cost analysis" Bonfring international journal of power system and integrated circuits, vol. 1, special issues, December 2011.

[6] Nagaraj Balijepalli, Subrahmanyam S. Venkata, Charles W. Richter, Richard D. Christie, Vito J. Longo " Distribution system reliability assesment due to lighting storm' IEEE transaction on power delivery, Vol. 20, No.3, July 2005.

[7] R. E. Brown, S. Gupta, R.D Christie, S.S. Venkata, R. Fletcher " distribution system reliability assesment: momentary interruptions and storms" IEEE transaction on power delivery, Vol.12, No. 4, October 1997.

[8] A. Onen "Model-Based Grid Modernization Economic Evaluation Framework, Ph.D. Dissertation, Virginia Polytechnic Institute and State University, March 2014.

[9] D. Cheng,A Onen,J Jung,R Arghandeh,R Broadwater, "Model Centric Approach for Monte Carlo Assessment of Storm Restoration and Smart Grid Automation", ASME Power 2014 Conference, Baltimoe, Maryland, USA, August 2014, pages 1-6.

[10] David Kleppinger, Robert Broadwater, Charlie Scibona, "Generic reconfiguration for restoration" in Elsevier Electric Power System Research, volume 80 issue 3, march 2010, pages 287-295.

[11] Josh Hambrick, Robert Broadwater, "Configurable, Hierarchical, Model-based Control of Electrical Distribution Circuits", IEEE Transactions on Power Systems, Pages Volume:26, Number:3, August 2011, Pages 1072-1079.

[12] Ahmet Onen, Jeremy Woyak, Reza Arghandeh, Jaesung Jung, Charlie Scirbona, and Robert P. Broadwater, "Time-varying Cost of Loss Evaluation in Distribution Networks Using Market Marginal Price," International Journal of Electrical Power and Energy Systems, Elsevier, vol. 62, pages 712-717, June, 2014.

*[13]* Tanuj Manglani, Y.S Shishodia, "A survey of optimal capacitor placement techniques on distribution lines to reduce losses", *International Journal of Recent Research and Review, Vol. I, March 2012*

[14] M. Dilek, R. Broadwater, "An Introduction to Integrated Design in Electrical Distribution," Proceedings of PES 2002 Winter Meeting, January 27-31, 2002, New York, NY.

[15] Thomas H. Fritts, "Economic cost of electrical system instability and power outages caused by snakes on the Island of Guam", International Biodeterioration & Biodegradation 49 (2002) 93 – 100.

[16] T. Wilson, "Energy Conservation with Voltage Reduction-Fact or Fantasy", IEEE Rural Electric Power Conference, 2002.