Distribution grid reconfiguration reduces power losses and helps integrate renewables

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Abstract: A reconfigurable network can change its topology by opening and closing switches on power lines. We use real wind, solar, load, and cost data and a model of a reconfigurable distribution grid to show that reconfiguration allows a grid operator to reduce operational losses as well as accept more intermittent renewable generation than a static configuration can. Net present value analysis of automated switch technology shows that the return on investment is negative for this test network when considering only loss reduction, but that the investment is attractive under certain conditions when reconfiguration is used to minimize curtailment.

Keywords: distribution networks, reconfiguration, renewables

1. Introduction

A reconfigurable network can change its topology by opening and closing switches on power lines. Distribution network reconfiguration is interesting because it allows the grid to operate with lower resistive losses or transmit more power from distributed generation than in static configurations, by dynamically changing its topology in response to changes in load and distributed generation. This technique has been employed in Portugal and other EU countries, and experimentally in the U.S.[1]

Some distribution companies have added or are planning to add significant amounts of distributed generation (DG), such as solar, wind, or natural gas microturbines to their networks. Because of the variability of wind and solar, these networks may experience severe fluctuations in generation. Here we examine whether the loss-minimizing configuration of the network could change depending on the output of wind or solar generation. We also examine whether reconfiguring the network could maximize the use of renewable generation by reducing wind or solar curtailment that would otherwise be necessary due to the finite capacity of the lines and bounded voltages of the nodes. Our research contributes to the field of network reconfiguration because it uses real load, wind, and solar generation data, wind forecasts, and prices to calculate reductions in power losses and costs over time.

Reconfiguration is important because sometimes changing the topology of an electrical network reduces operational power losses (Baran and Wu, 1989;

Shirmohammadi and Hong, 1989; Glamocanin, 1990; Taleski and Rajicic, 1997). A network operator might also avoid a voltage or line capacity violation by reconfiguring the grid topology: by changing the electrical path of least impedance, lines transmit more or less electricity and nodes receive power at different voltages (Kashem et al., 2000). Reconfiguration can also assist distribution network operators with service restoration after an outage (Shirmohammadi, 1992) and with avoiding service interruptions and associated penalties (Carvalho et al., 2007; Nabaei et al., 2010).

When there is DG in a network, reconfiguration can also lower losses and prevent voltage or current violations that the DG might have otherwise caused (Choi et al., 2003; Celli et al., 2005). If the DG produces power at a rate near that of the demand of the system, then the minimum loss configuration will accommodate the DG as if it were the main power source of the grid. This will likely be a different configuration than when most of the power is coming from the high voltage grid, especially if the DG is located far from the high voltage connection. When the DG introduces more variability, as is the case with wind turbines or solar photovoltaic (PV), the potential for loss reduction through reconfiguration is even greater due to a frequently changing distribution of load over the grid topology. Recent work has shown that reconfiguration can reduce losses of a network with distributed solar PV (Subrahmanyam and Radhakrishna, 2010a) and wind (Subrahmanyam and Radhakrishna, 2010b), but this work does not use time series data.

Due to daily and seasonal variations in load, reconfiguring the distribution network at various intervals throughout the day and year can increase the efficiency of the grid by reducing power losses. Previous work has shown that reconfiguration throughout a day decreases power losses (Broadwater, Khan, Shaalan, & Lee, 1993; Lopez, Opazo, Garcia, & Bastard, 2004). Also, researchers have extended the analysis of loss reduction to include cost savings (Zhou et al., 1997). Our research extends the application of real load and price data to reconfiguration by using 2008-2010 Electric Reliability Council of Texas (ERCOT) load and price data ("ERCOT - Hourly Load Data Archives," 2011), wind data and forecasts from a Great Plains wind farm (supplied on the condition of anonymity), and solar PV generation data from a utility-scale array in Arizona[2]. The characteristics of real renewable generation, load, and price data are not easily modeled by simple distributions, so the use of actual data is a required step in determining if distribution network reconfiguration is likely to lead to practical loss reductions.

Another branch of the literature on distribution network reconfiguration deals with algorithms to search for the lowest-loss radial configuration. Researchers have explored the use of evolutionary algorithms (Carvalho et al., 2001; Chiou et al., 2005) as well as genetic algorithms to find efficient configurations (Nara et al., 1992; Mendoza et al., 2006; de Queiroz and Lyra, 2006). Other techniques used include particle swarm optimization (Olamaei et al., 2007; 2008), simulated annealing (Chiang and Jean-Jumeau, 1990; Jeon et al., 2002), and decomposition (Carvalho et al., 2005). Rather than use one of these algorithms to solve for the lowest-loss configuration in each time interval, we take advantage of the small size of our test distribution network and calculate results for each plausible radial configuration and choose the one with lowest losses, or alternatively the one that results in the smallest curtailment of wind. The aim is to determine the approximate magnitude of loss reduction or increase in DG accommodated, and to examine the sensitivity of the result to the time interval between reconfigurations.

Our work is new because we explore the loss- and cost- reducing benefits of network reconfiguration at different frequencies over months or a year, taking forecasts into account. We look at whether a grid operator can accept more power from a wind or solar PV plant over a year with reconfiguration than with a static network, and examine the penetration level of wind and solar power at which reconfiguration begins to make a difference. We also explore the return on investment of reconfiguration technology.

1.1 Summary of Results

We find that grid operators can reduce their resistive line losses as well as the cost of losses by 10-15% through reconfiguration when solar PV provides ~30% of the energy. A network with a 50% penetration of wind may be able to reduce losses using reconfiguration by 30%; smaller benefits from reconfiguration are observed with less than ~50% of system energy supplied by wind. In a scenario without DG, reconfiguration does not significantly reduce losses, but different base configurations have significantly different losses throughout the year. With perfect wind information, increasing the interval between reconfigurations from 5 minutes to 60 minutes negligibly degrades loss reduction; increasing it from 60 minutes to 24 hours degrades loss reduction from around 30% to around 20%. When forecasts inform reconfiguration decisions, the resulting savings decrease by 10-15% compared to perfect information (we do not have solar forecast data, so present forecast implications are only for wind). Reconfiguration allows the grid operator to curtail significantly less wind or solar generation than would be necessary without reconfiguration, depending on the magnitude of the DG resource. This benefit begins at about 30% solar PV penetration by total energy, or 70% wind penetration by total energy. The reconfiguration technology has a negative return on investment when considering just loss reduction, but is positive when using reconfiguration to reduce wind curtailment.

1.2 Overview of Paper

Section 2 describes the methods and data sets, and the limitations that each confers on the results of our analysis. Section 3 contains a detailed description of results and Section 4 describes sensitivity analyses. Section 5 contains the results of an examination of the economics of reconfiguration. In Section 6 we present the policy implications of this research. Section 7 contains the conclusions we draw from the results of this research.

2. Methods

2.1 Data

We modeled the distribution network with typical line characteristics for a medium voltage network (Appendix C). Load data come from 2008-2010 ERCOT (Electric Reliability Council of Texas) records ("ERCOT - Hourly Load Data Archives," 2011). For wind data and forecasts, we use data from a U.S. wind farm in the Great Plains (supplied on the condition of anonymity). The data consist of hourly wind power outputs and 84-hour outlook forecasts generated every 6 hours for 2008 and 2009. Due to a change in reporting style, forecasts from only the first five months of 2008 were useable for this research. Solar data came from the 5 MW Springerville array in eastern Arizona. No forecasts for solar data were available. For load forecasts, we use a two-week rolling average of each one-hour interval. For example, to predict the load from 1:00 am – 2:00 am, we average the past two weeks' loads from 1:00 am – 2:00 am.

Prices for the model come from 2008-2010 ERCOT data for the hourly price of electricity ("ERCOT - Balancing Energy Services Market Clearing Prices for Energy," 2010).

In addition, we have load profiles for adjacent feeders from the Lisbon, Portugal metropolitan area to characterize the correlation of demand at different nodes over time.

2.1.1 Limitations and Assumptions

We use North American data on loads, wind, and prices to simulate the Portuguese electricity system, because Portuguese data were unavailable. The Great Plains wind forecasts record an 84-hour outlook for hours *t* through *t*+84 for the first five months of 2008. For the rest of 2008 and 2009, the 84-hour outlook is for hours *t*+3 through *t*+84. Therefore, we only use the first five months of 2008 data for the analysis using the Great Plains wind farm forecasts. This means that for analysis using wind data, the model spans only five months.

2.2 Model

A simple model of an electricity distribution network consists of busses representing loads, generators, and high voltage bus connections. Power lines connect the busses, transmitting electricity from sources to sinks. We define a reconfigurable network as one that can change its topology by opening and closing switches on the power lines. In this paper, we further restrict the discussion to radial distribution networks: networks in which each “child” node has only one “parent” node. We use a modified version of the 13-node IEEE distribution test feeder in our model. Figure 1 shows the original IEEE 13-node distribution test feeder. Figure 2 shows the additional lines we add to the network to enable a meaningful reconfiguration investigation. Figure 3 shows the modified network; we removed the transformer between nodes 633 and 634 to simplify the problem, added a distributed generator at node 611 and replaced the voltage regulation transformer between node 650 and node 632 with an infinite bus. Figure 4 shows an example of an alternative configuration. For diagrams of all alternative configurations, see Appendix A: Configuration Diagrams.

Figure 1. Original IEEE 13-node Test Feeder (circle with arrow represents a generator; symbol between 633 and 634 is a transformer)

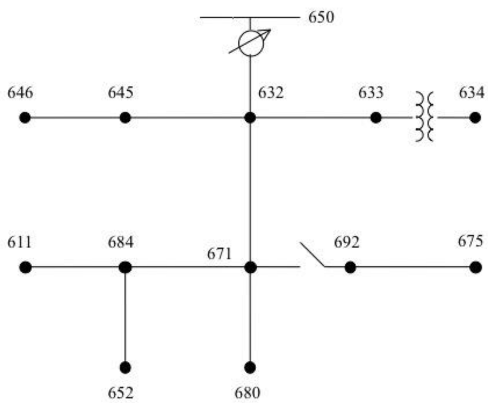


Figure 2. Modifications to IEEE 13-node Test Feeder (generator is replaced by infinite bus; transformer removed to simplify the model)

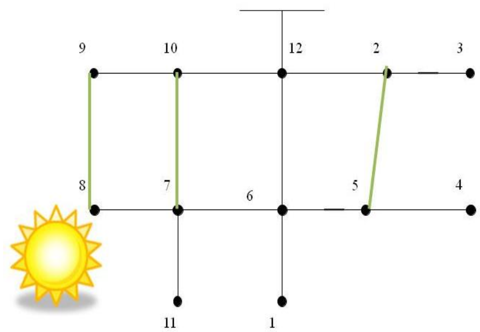


Figure 3. Modified 13-node Feeder, base configuration

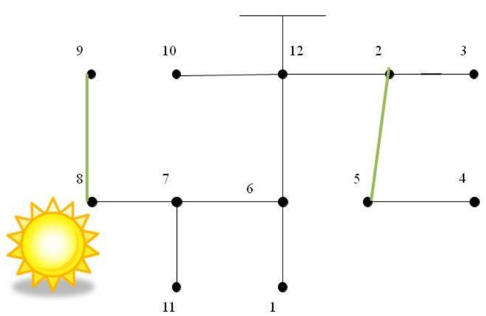
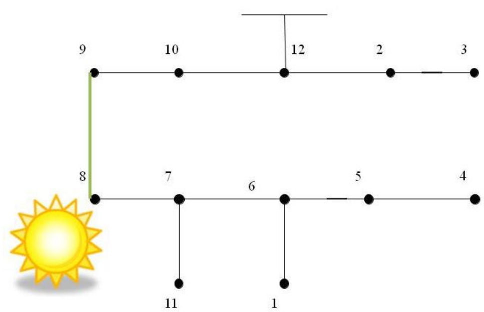


Figure 4. Alternative Configuration to IEEE 13-node Test Feeder



We use the backwards-forwards sweep method to iteratively solve for the voltages, currents, and total demand of a radial distribution network (Shirmohammadi et al., 1988; Zimmerman, Hsiao-Dong Chiang, 1995; Rajicic and Dimitrovski, 2001; Afsari et al., 2002; Liu et al., 2008; Augugliaro et al., 2010). The backwards-forwards sweep method is an iterative power flow solution for radial networks. Starting node voltages are set to a predefined value (for example, 1 per unit), and the source node is considered a fixed voltage source. The first iteration begins at the end-nodes and adds up the shunt and line currents to the branches from child nodes to their network parents. Then the algorithm calculates voltages "forwards" from parent to child nodes accounting for voltage drops for the currents calculated previously and compares the voltages at nodes in iteration v to those in iteration $v-1$. When the difference between the old and new voltages is smaller than a certain threshold for all nodes, the algorithm stops and reports the final branch currents, node voltages, and total network demand. Configurations with node voltages outside a specified range, or configurations that do not converge[3] within 25 iterations, are discarded. Of the remaining configurations, the model calculates the difference in demand between a base configuration and the alternatives and selects the configuration with the lowest losses in each time interval.

There are 60 possible configurations of the model network. By examining the results of all of the configurations in a variety of loading situations, all but 18 were eliminated because they were either never or rarely the loss-minimizing configuration. The difference between loss reduction using all 60 configurations and using only the best 18 configurations is not significant (Table 1).

Table 1. Difference in loss reduction when using 60 and 18 configurations.

Frequency of Reconfiguration (hours)	60 configurations	18 configurations
1	29.53%	29.40%
2	28.18%	28.13%
3	27.36%	27.32%
4	26.69%	26.66%

5	25.93%	25.89%
6	25.41%	25.38%
12	22.09%	22.07%
24	18.92%	18.91%

One output of the model is the percent reduction in losses between the base case scenario (a non-reconfigurable grid) and the scenario with switching at specified intervals. The model considers losses in three scenarios (Table 2).

Table 2. Model definitions for line losses in different scenarios of solar or wind distributed generation.

Scenario	**Definition of loss**
No solar or wind	Losses = Electricity drawn from HV grid – Load
Load is greater than solar or wind	Losses = Solar or Wind + Electricity drawn from HV grid – Load
Solar or wind is greater than load	Losses = Solar or Wind – Electricity drawn from HV grid – Load

When the DG produces more electricity than there is demand, the extra electricity is transmitted back to the high voltage grid. The model also considers prices at each hour of operation and calculates how much a utility would save from loss reduction over the course of a year using reconfiguration. The model multiplies the cost of electricity for an hour by the loss savings in the hour to calculate this.

2.2.1 Limitations and Assumptions

We divide the test feeder into four zones, each of which contains 2-4 nodes (see Figure 5). Total hourly load for the test feeder is determined by dividing the total ERCOT load by 100 to scale the load appropriately for the size of the IEEE test system. Load is divided among the zones by multiplying that quotient by correlated random variables, and then normalized so that the total load of the feeder is still equal to the same fraction of ERCOT load. We correlate the random variables by using a Cholesky factorization with a correlation of 0.5. Within a zone, we evenly divide the load. In a sensitivity analysis, we examine the effects of using a perfectly correlated data set as well as a data set with no correlation. We also use 24-hour load data from 11 feeders in Lisbon with Bonneville Power Administration (BPA) wind data to simulate realistic feeder correlations (see Appendix B: Load Correlation Across the Network) ("BPA: Balancing Authority Load & Total Wind Generation," 2010). Both analyses support the hypothesis that using an 0.5 correlation with the ERCOT load data is a reasonable assumption.

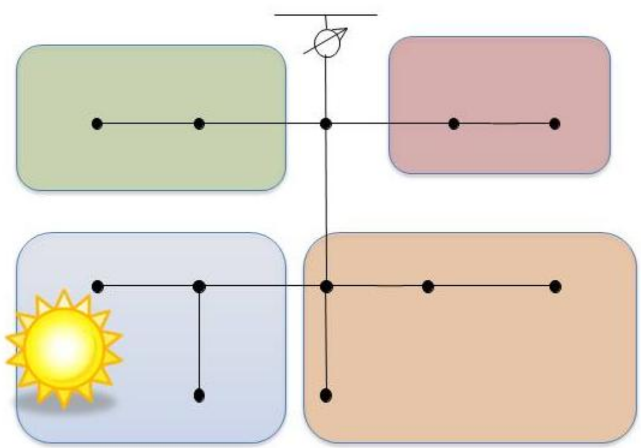


Figure 5. Zones of equal load in the test feeder

As this is not a continuous power flow model, the outputs of voltage, current, and total demand are not perfect. This model cannot account for second-to-second variations in demand or wind power output. Rather, it assumes outputs to be constant for at least 5-minute intervals.

We also assume that the high voltage grid connected to our model can accept all of the excess electricity in each time interval without significant changes in voltage magnitude. We assume that all lines can accept the radial flow of electricity in both directions within the constraint of a current limit.

We get solar generation data from an Arizona 4590 kW solar array. The average output of the array is 867 kW for the 8760 hours in 2005. We scale the array to fit our sample grid by multiplying the output of the array in each hour by a factor between 1.3 (10% penetration by total energy demand) and 13 (100% penetration by total energy demand).

Wind data from the Great Plains wind farm is scaled down to represent a smaller wind farm. We scale down the output of the Great Plains wind farm varies to represent different penetrations of wind in the system. In reality a smaller wind farm would likely have higher intermittency and variability than the full-sized wind farm.

With these assumptions, it is important to ask how applicable our results are to real distribution grids and wind farms. By using months of solar, wind, load data and forecasts, our model more closely mimics a real system than other models that only consider one point in time or a short period of variable load. Also, the levels of loss reduction from reconfiguration in our model correspond to those found by Fisher, O'Neill and Ferris using transmission lines (Fisher et al., 2008).

3. Results: Engineering Analysis

3.1 Reconfiguration Can Reduce Losses and Operating Costs of Losses

We find that grids with DG from solar photovoltaic (PV) cells benefit from reconfiguration. Electricity from solar photovoltaic cells is intermittent and variable. The cells produce no electricity at night, and during the day produce electricity at a rate proportional to the angle of the sun in the sky, interrupted by clouds. A network with 20% DG in the form of a solar PV plant may be able to reduce losses using reconfiguration by up to 15%; when DG penetration reaches 30% the network may be able to reduce losses by up to 18%. For penetrations higher than 30%, line current violations occur frequently and it becomes more beneficial to focus on curtailment reduction than loss reduction (Section 3.2).

A network with 50% wind penetration can reduce losses by approximately 30%, and similarly reduces the cost of losses by ~ 25%, by using reconfiguration. Analysis of load and price data from 2008-2010 shows that loss and cost reduction fall within a small range. The loss reduction benefits from reconfiguration degrade for networks with lower than 50% wind penetration by total energy (Figure 6). A network without intermittent DG cannot expect to reduce losses significantly with reconfiguration unless the base configuration is not optimal for the power flow.

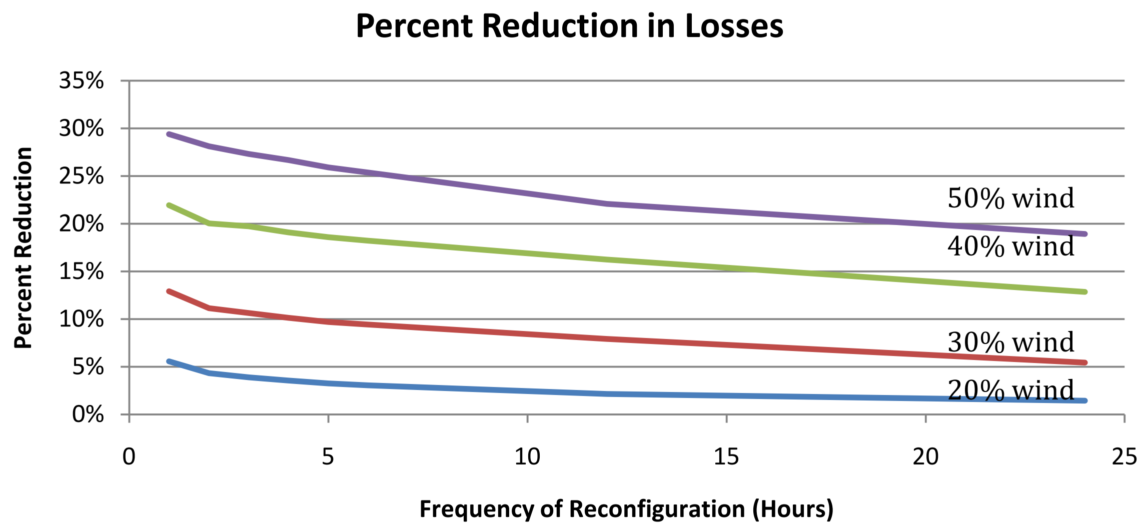


Figure 6. Percent loss reduction for different distribution system reconfiguration frequencies for West Texas 2010 load and price data.

Loss reduction potential for wind DG and solar DG at 30% penetration by total energy is similar. The benefit of loss reduction through reconfiguration for wind DG extends to higher penetrations than for solar DG because of the peakiness of the solar curve compared to the wind curve (Figure 7). At peak production, the solar array produces about two thirds more power than the wind farm does for equivalent penetrations. The network does not have the capacity to accommodate all of the generation from the solar array, so at higher than 30% penetration, the major benefits from reconfiguration are avoiding line current violations and avoiding solar curtailment (Section 3.2).

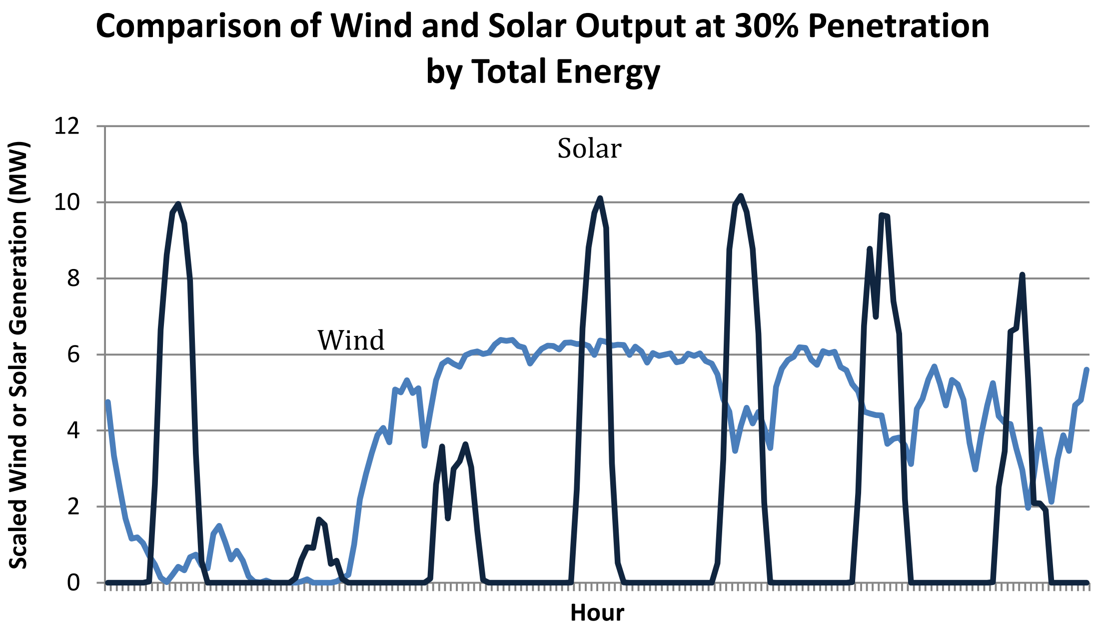


Figure 7. Comparison of wind and solar outputs. While the area under the curves is equivalent, the high peaks in solar cause the network to curtail its generation more frequently than for wind. Each tick mark represents one hour.

3.2 Reconfiguration Allows Grids to Accept More Intermittent DG

When solar penetration increases, reconfiguration allows the grid operator to curtail less electricity than would be necessary without reconfiguration (Figure 8). To simulate solar curtailment, we constrained the power flow solution to reject a solution that exceeds a current limit in one or more of the lines. Rather than curtail all DG in an interval with a line capacity violation, the model reduces the amount of solar or wind by 10% until the capacity violation is resolved or until the solar or wind is completely curtailed in that configuration for that hour. For the system with solar DG, the static network can accept virtually all the electricity from the solar array until it satisfies about 30% of the total load in the system. For the system with wind DG, the static network can accept virtually all the electricity from the wind farm until it satisfies about 65% of the total load in the system. At higher DG penetrations, the reconfigurable network can accept significantly more solar or wind than the static network can.

We also look at the ability of the network to reduce curtailment for a wind farm using reconfiguration. At very high penetrations by total energy (65% and higher), reconfiguration allows the system to accept significantly more wind than a non-reconfigurable system can (Figure 9).

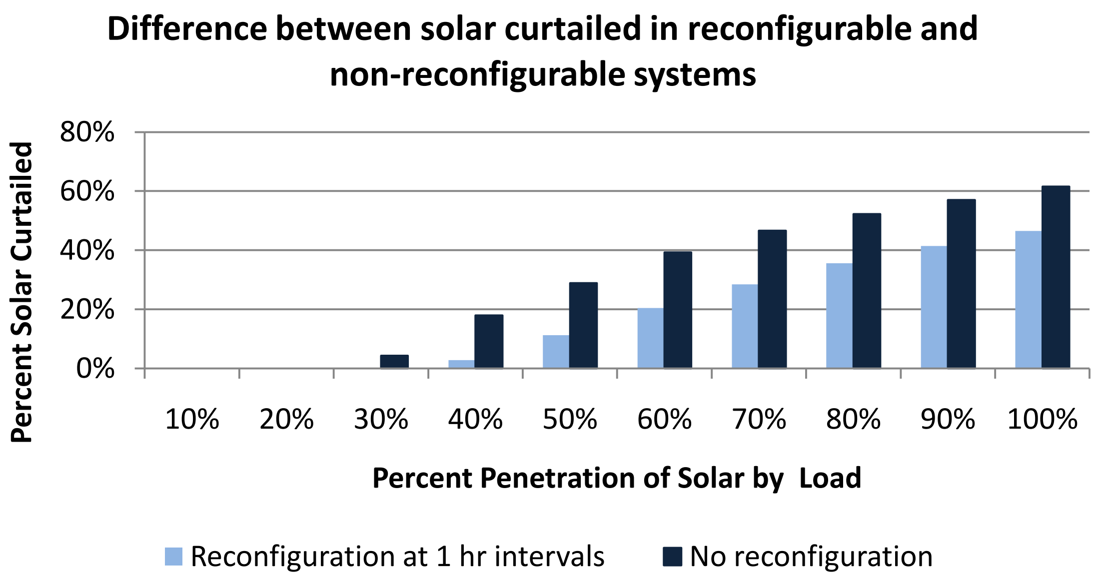


Figure 8. Solar curtailment reduction, reconfiguration at 1-hr intervals.

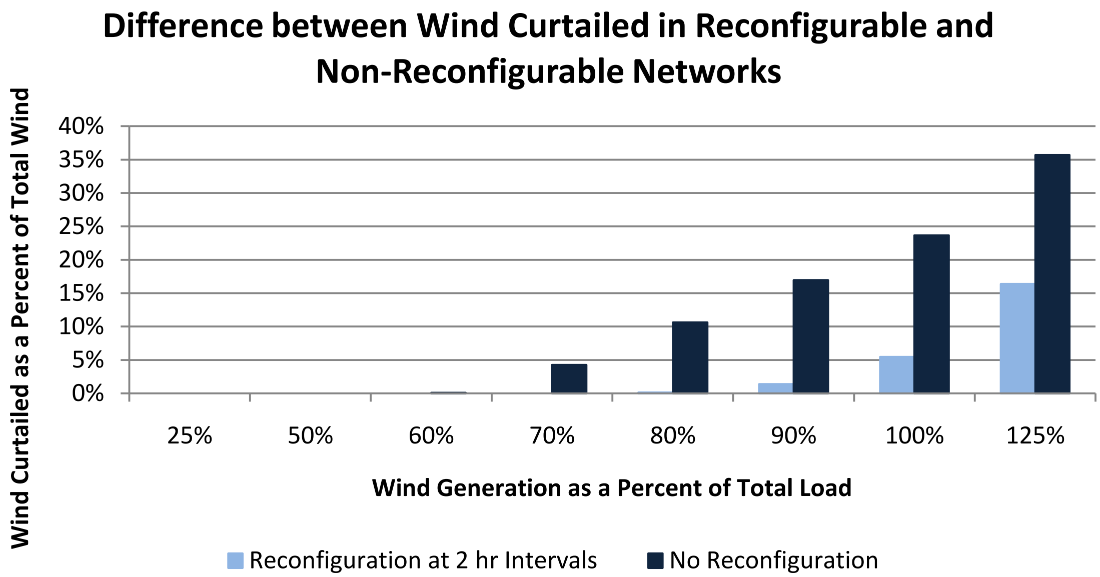


Figure 9. Reconfigurable networks require less wind curtailment than non-reconfigurable networks when the generation of wind satisfies about 70% of total demand.

A common way to purchase power from a wind farm is through a power purchase agreement, or PPA. Through a PPA, a load serving entity (LSE), such as our sample grid, agrees to purchase wind produced from the wind farm at a set price for a set period of time. In general, the PPA contains a "take or pay" clause, which requires the LSE to purchase all the power that the wind farm produces regardless of whether there is sufficient load or congestion in the lines.

Under a typical PPA, the grid operator in our model would always be better off maximizing the amount of wind it takes rather than minimizing losses. If the set price in the PPA is much lower than the market price for electricity, the grid operator saves money by reconfiguring to accept more wind. If the set price is much higher than the market price, the grid operator will need to pay it anyway, so it is better to take more wind to avoid purchasing power from the high voltage grid.

Penalties for failing to meet a renewable portfolio standard would only strengthen this conclusion. Figure 10 shows the potential savings for using reconfiguration to avoid wind curtailment in a network with varying degrees of wind penetration and different PPA set prices. The price for electricity from the high voltage grid comes from ERCOT 2010 price data ("ERCOT - Balancing Energy Services Market Clearing Prices for Energy," 2010).

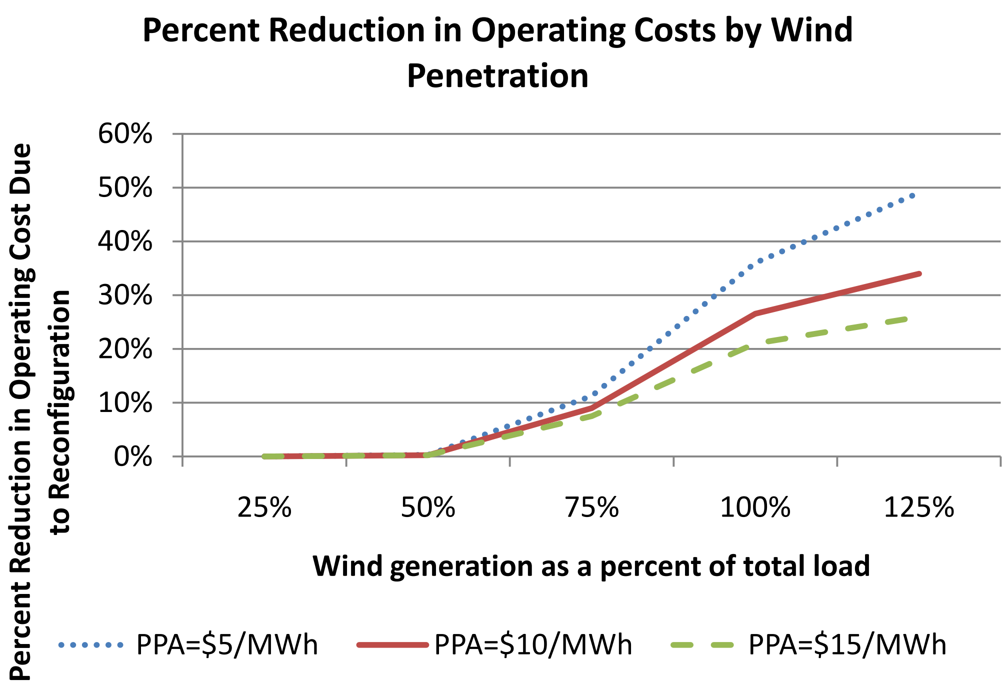


Figure 10. Operating cost reductions using reconfiguration to reduce wind curtailment, reconfiguration at 2-hr intervals.

4. Sensitivity Analysis

4.1 Interval between reconfigurations

Because reconfigurations result in fatigue on the switches, grid operators should limit the frequency of reconfigurations. While reconfiguring less frequently will help avoid wear on the switches, the grid operator sacrifices some of the loss savings due to lower accuracy of wind and load forecasts for longer intervals, as well as the variability of wind and load during longer intervals.

By varying the interval between reconfigurations from one hour to 24 hours, we find that, for a scenario with perfect information, the grid operator sacrifices only about 3% of the potential loss reduction by reconfiguring every 6 hours rather than every hour. This means the grid operator may avoid unnecessary fatigue on the switches by reconfiguring less often. Figure 11 shows how varying the interval between reconfigurations affects the loss reduction of the system. Even at intervals of 24 hours, the grid operator can reduce losses by around 20% if he could predict with perfect accuracy the loads and wind for the next 24 hours. The percent reduction in the cost of losses follows a similar pattern as loss reduction but is more variable because of the variations of average electricity price in ERCOT in different regions and years (Figure 12).

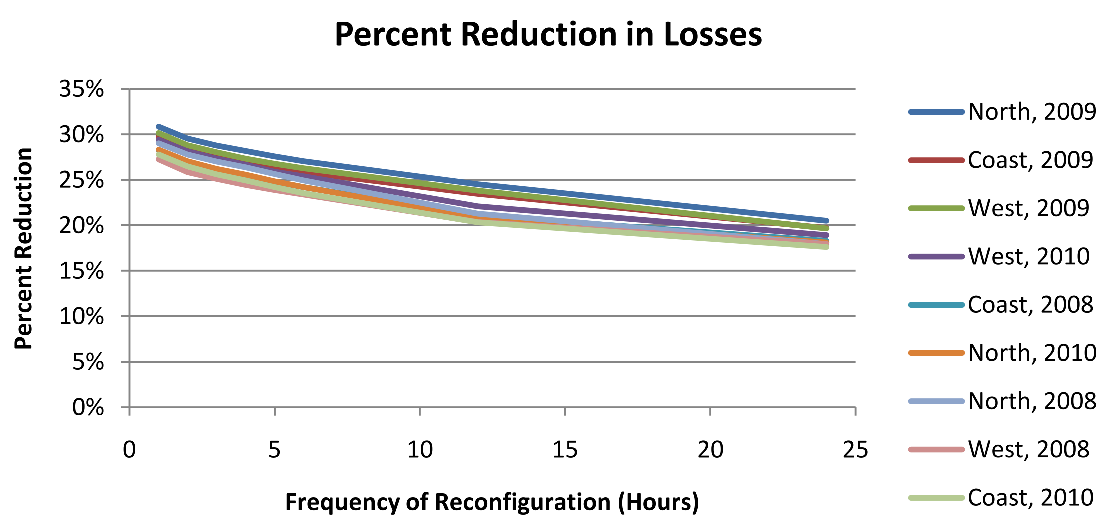


Figure 11. Reduction in losses from reconfiguration, using data from different regions and years within ERCOT, 50% wind penetration by total energy.

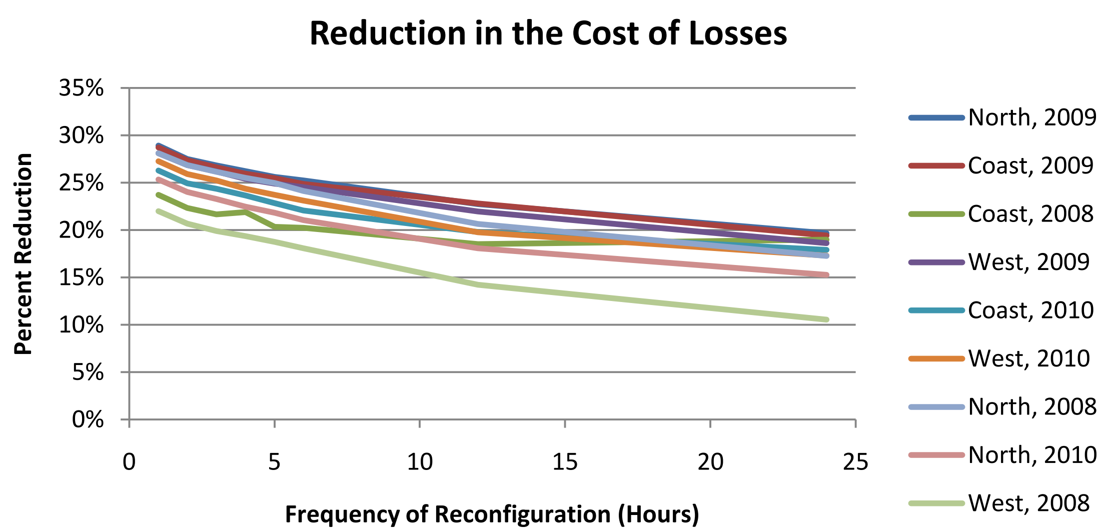


Figure 12. Reduction in the cost of losses from reconfiguration, using data from different regions and years within ERCOT, 50% wind penetration by total energy.

4.2 Reconfiguration at High Frequencies Does Not Significantly Improve Loss Reduction

As a first analysis, we used 5-minute BPA wind, load, and forecast data to examine loss reduction with reconfiguration. However, the result of varying the frequency of reconfiguration between 5 minutes and one hour shows that there was not a significant difference in loss reduction at frequencies of less than one hour (Figure 13). Since reconfiguring more frequently reduces the lifetime of the switches, it is better to choose a lower reconfiguration frequency if the difference in loss reduction is not significant.

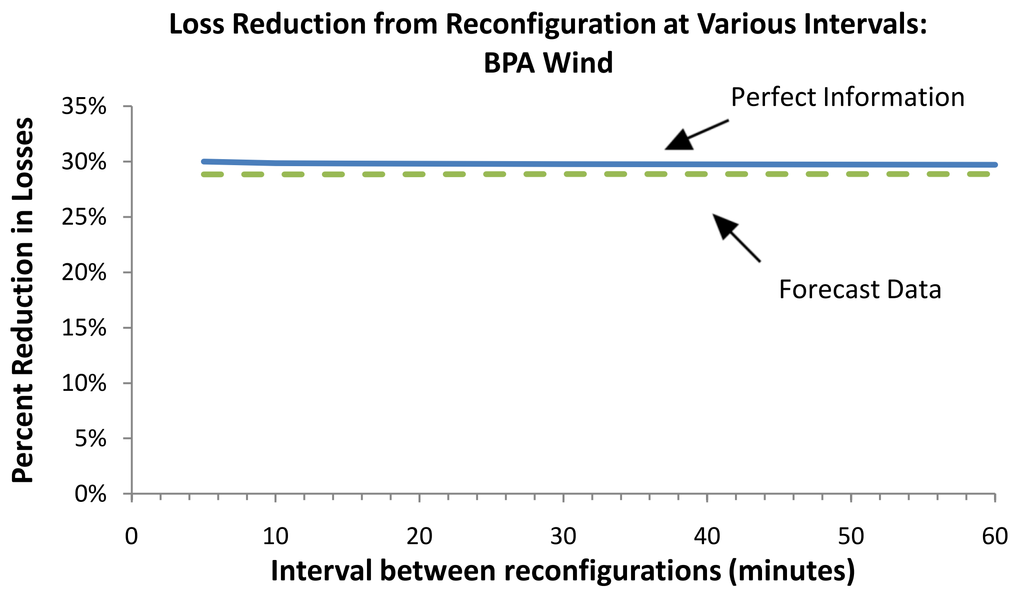


Figure 13. Loss reduction from reconfiguration at intervals of less than one hour; 50% wind penetration by total energy.

4.3 Reconfiguration based on forecasts of wind and load

Modeling grid operations without perfect information and comparing the results to an operator who has perfect information shows how the reconfiguration model might operate in a real situation. Using wind power forecast data from a Great Plains wind farm, and reconfiguring at a frequency of one hour, the operator using wind and load forecasts reduces losses by 5% less than the clairvoyant operator (Figure 14). When the interval between reconfigurations is larger than one hour, the percent difference in loss reduction between perfect and forecast information does not change significantly. A possible explanation for this is because reconfiguring every 12 or 24 hours already requires a sacrifice in loss reduction (due to variability during the period between reconfigurations), using the forecasts instead of perfect information is not the dominant reason for poorer performance.

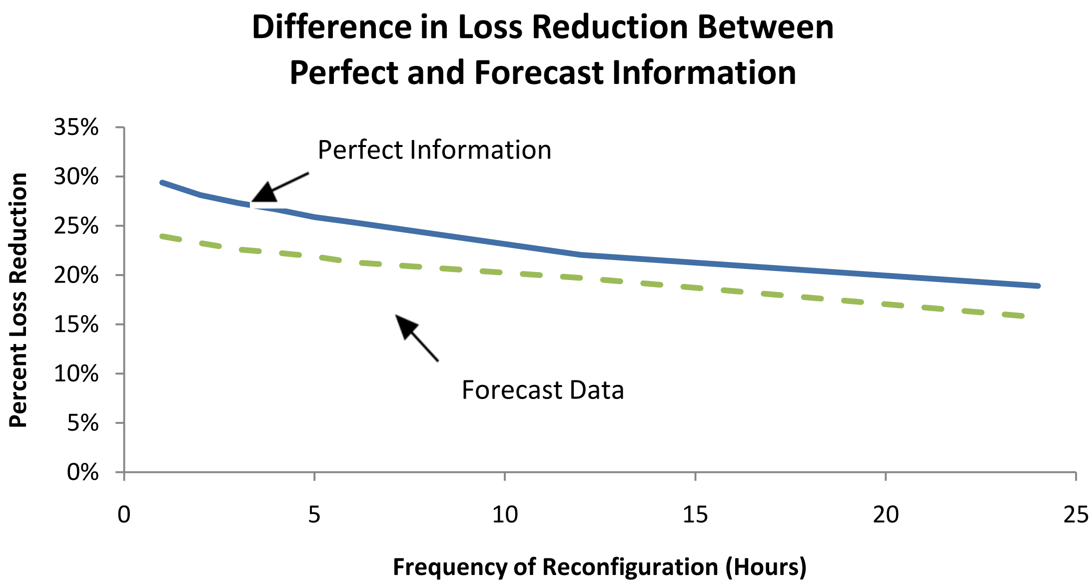


Figure 14. Reduction in losses using perfect information and forecasts, West Texas 2010 load data. Wind data from Great Plains wind farm, 50% penetration by total energy.

4.4 Changing the Location of the Distributed Generation

Depending on the location of the DG in the network, the potential for loss reduction changes. In this network, a wind farm at node 8 confers the largest potential loss reduction through reconfiguration compared to the static configuration with lowest losses. In contrast, a wind farm at node 1 or node 10 has less potential for loss reduction (Figure 15 and Figure 16). The same pattern emerges for the DG solar array: the loss reduction potential during a year of operation with 30% solar penetration by total energy is 18%, 11%, and 8 % for an array at node 8, node 10, and node 1 respectively.

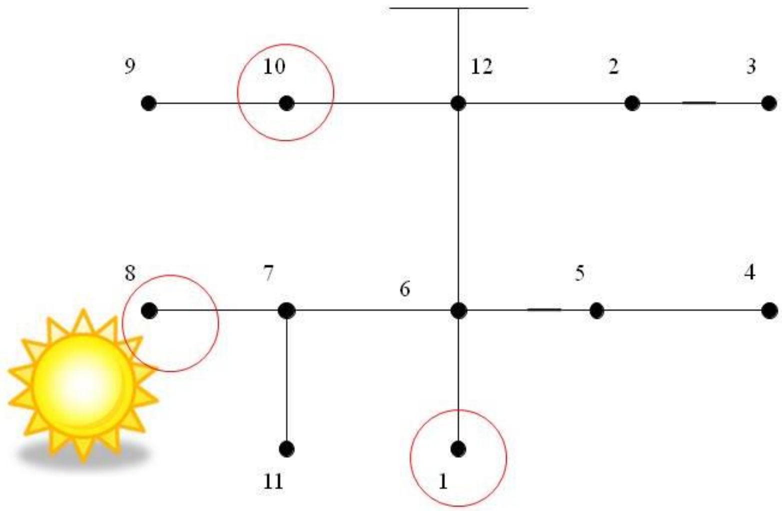


Figure 15. Sample network with alternative wind farm locations circled. Node 8 is the standard location for the wind or solar DG resource throughout this analysis.

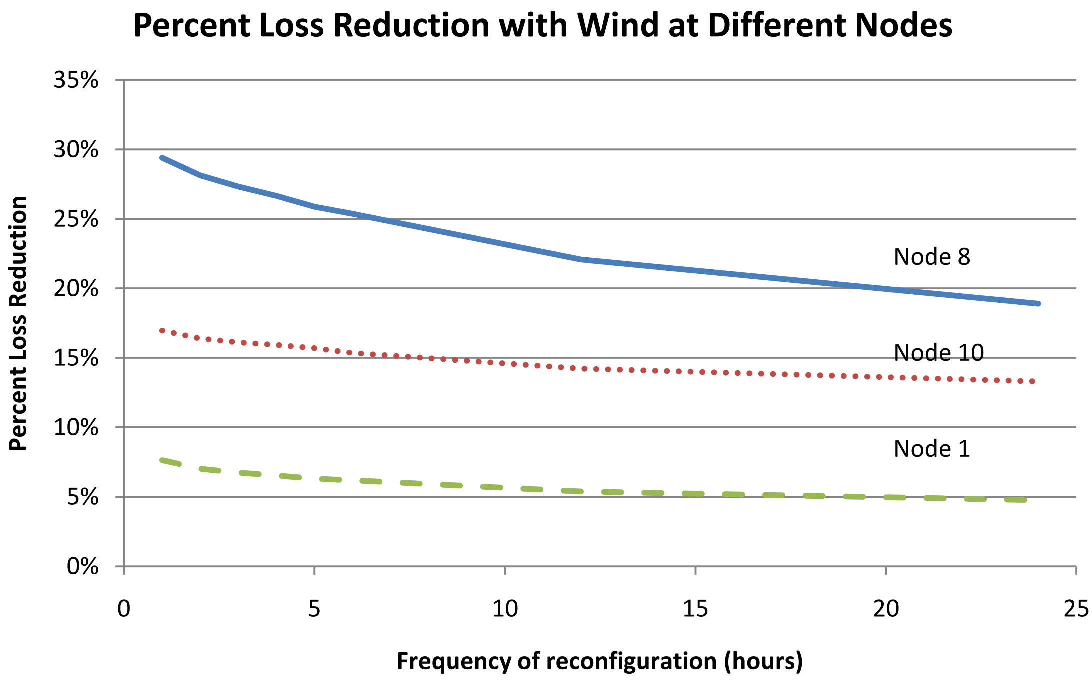


Figure 16. Effect of changing the location of the wind farm on loss reduction.

5. Results: Financial Analysis

5.1 Net Present Value Analysis

The interval between reconfigurations determines the expected lifespan of the switch based on an expected 10,000 actuations per switch. With this information and the capital costs of the switches and automation technology, one can calculate the net present value of an investment in reconfiguration technology for the test network. For the NPV analysis and sensitivity analysis we use the values in Table 3 and a 20-year outlook.

Table 3. Values used in NPV analysis.

Item	Best Estimate	Source
Price of switch	$10,000	(Stoupis, 2010)
Price of actuator	$3,000	(Stoupis, 2010)
Average lifetime of switch and actuator (in actuations)	10,000	(Stoupis, 2010)
Discount rate	10%	

The savings a grid operator experiences depend on how often he reconfigures the network throughout the day. Using the Great Plains wind forecasts and ERCOT load forecasts and price data from 2010, we calculate the annual cost savings for each reconfiguration frequency (Table 4).

Table 4. Annual cost savings expected through reconfiguration at different intervals. Assumes 70% wind penetration for the wind curtailment scenario and 50% wind penetration for the loss reduction scenario.

Hours between Reconfigurations	Savings per year (forecast, wind curtailment)	Savings per year (forecast, loss reduction)
1	$88,400	$4,700
2	$88,400	$4,500
3	$87,900	$4,400
4	$87,800	$4,300

5	$87,300	$4,300
6	$87,300	$4,100
12	$80,300	$3,700
24	$74,700	$2,900

Based on the annual cost savings and the cost of switch installation and replacement over the 20-year period, Table 5 shows the expected NPV of the investment based on the objective of the reconfiguration (avoiding wind curtailment or loss reduction) and the number of hours between reconfigurations. The results do not follow a monotonic trend because reconfiguring at short intervals creates higher savings, but it also results more frequent switch replacement, which adds to capital costs. The result in Table 5 shows that the return on investment when avoiding wind curtailment is very attractive, while the investment costs do not outweigh the monetary benefit of using the technology solely for loss reduction. For both scenarios, reconfiguring every 3-6 hours creates the highest NPV.

Table 5. Net Present Value Savings from Wind Curtailment Reduction and Loss Reduction, PPA=$10/MWh. Assumes 70% wind penetration for the wind curtailment scenario and 50% wind penetration for the loss reduction scenario.

Hours between Reconfigurations	NPV savings-costs wind curtailment	NPV savings-costs loss reduction
1	$560,000	$(150,000)
2	$610,000	$(110,000)
3	$630,000	$(80,000)
4	$630,000	$(80,000)
5	$620,000	$(80,000)
6	$630,000	$(80,000)
12	$570,000	$(90,000)
24	$520,000	$(90,000)

Although in Portugal and many other EU countries it is common to have meshed distribution networks in urban and semi-urban areas, other networks may require new lines in addition to switches to enable reconfiguration. Typical costs for new lines are listed in Table 6.

Table 6. Costs of Different Distribution Line Types (Carvalho, 2011)

	$/km	Cost of adding three lines to test network
ACSR Robin	$29,400	$57,330
ACSR Beaver	$36,400	$70,980
ACSR Partridge	$47,600	$92,820

The costs of new lines do not change the conclusion that using reconfiguration for loss reduction does not create a positive return on investment. It also does not affect the conclusion that using reconfiguration to avoid wind curtailment is a cost-effective use of the automated switches for this network only if the penetration of wind is very high (70% or greater).

6. Policy Implications

Reconfiguration reduces losses, making the entire electric power delivery system more efficient. The Energy Information Administration estimates electricity losses account for 6.6% of total energy use in the US electricity sector (Energy Information Administration, 2009). If a third of the losses are attributed to the medium voltage distribution system, eliminating 30% of those losses using reconfiguration is the equivalent of taking four 1000-MW coal-fired power plants operating at 60% capacity factor offline. If reconfiguration were widely used for loss reduction, a utility may be able to postpone building more generation capacity by improving efficiency instead. However, our results show that the loss reduction benefits of reconfiguration over time extend only to networks with significant renewable DG penetration (20-50%) at certain locations on the network.

Reducing losses and accepting more wind or solar generation imply that reconfiguration may reduce CO_2 emissions. However, more formal investigation taking into account the full portfolio of electricity generation for the grid would be needed to make an accurate assessment of CO_2 reduction potential.

Depending on the market structure in which the grid operates, benefits will accrue to stakeholders in different ways. Grid operators may reduce costs because they have reduced their losses. If the grid operates in a state with a renewable portfolio standard, and reconfiguration allows a grid operator to accept more of a renewable resource because the lines are congested less often, then the grid operator may benefit from purchasing fewer renewable electricity credits (RECs). If the utility has signed a PPA with the renewable electricity plant, being able to accept more of its electricity could save the utility in terms of operating costs. If the grid does not contain wind, grid operators still may consider whether the configuration of their network is optimal for delivering load with minimal losses.

Wind farm or solar PV plant operators not operating under a PPA will benefit if reconfiguration allows the grid to accept wind more often by reducing line congestion. The utility can purchase electricity from the renewable resource more often and the wind farm or solar PV plant operator gets higher revenue.

There is still a need for communication among wind generators, loads, switches, and the distribution control center to facilitate reconfiguration operations over time.

While cost savings may justify investment in reconfiguration for avoiding DG curtailment, there are also economic incentives to invest in efficiency. For example, distribution utilities in BPA can get reductions in wholesale electricity price for implementing efficiency measures (0.25 cents discount per kWh up to 70% of the capital expenditure) ("BPA - Energy Smart Utility Efficiency," 2010).

7. Conclusion

Using real solar, wind (forecast and actual), load, and price data we show that grid operators may be able to reduce operational power losses and accept more solar or wind generation using reconfiguration. At the current cost of reconfiguration technology, a net present value analysis shows that loss reduction alone is not enough to warrant investment in switches. However, the results show that reconfiguration would allow an LSE to cost-effectively get more value out of a PPA with a wind farm or solar array, if the penetration of the renewable DG in the system is over a certain threshold. Impending Renewable Portfolio Standard requirements would strengthen the argument for using reconfiguration to reduce renewable resource curtailment.

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Energy Information Administration, 2009. Table 8.1 Electricity Overview, 1949-2009 (Billion Kilowatthours). URL http://www.eia.doe.gov/emeu/aer/txt/ptb0801.html
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10. Appendix A: Configuration Diagrams

The following figures represent the different configurations of the network.

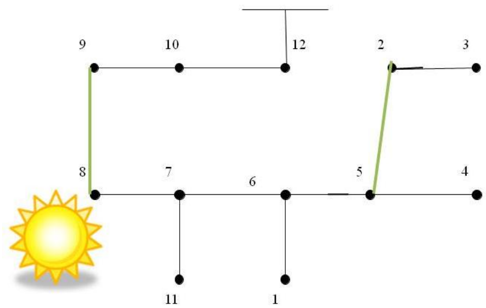


Figure 17. Configuration 1

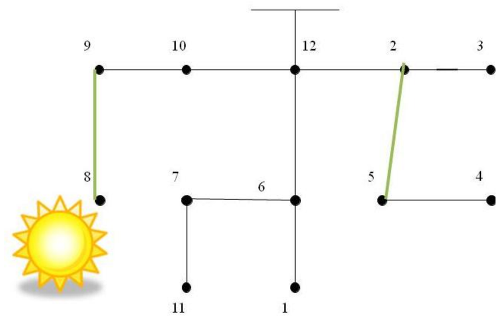


Figure 18. Configuration 2

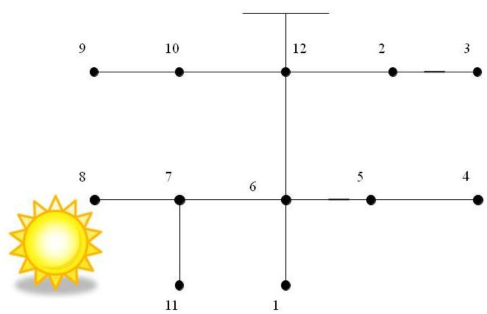


Figure 19. Configuration 3

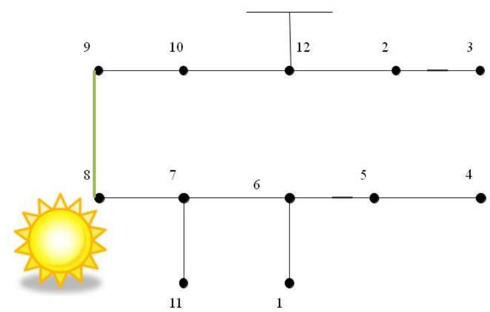
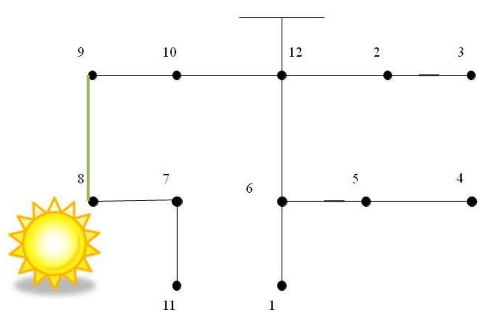


Figure 20. Configuration 4



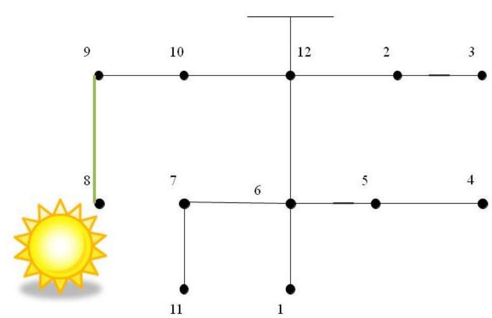
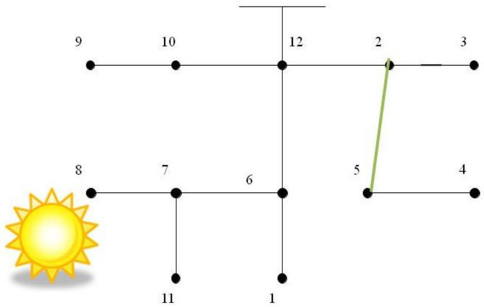


Figure 21. Configuration 5 **Figure 22. Configuration 6**



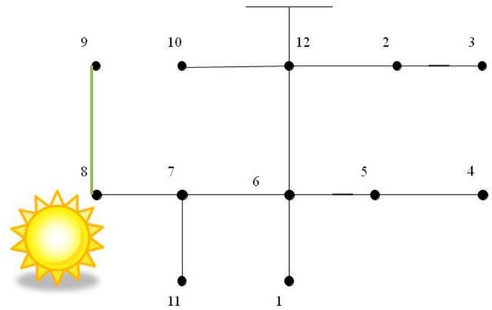
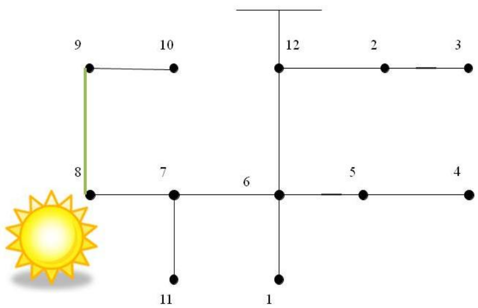


Figure 23. Configuration 7 **Figure 24. Configuration 8**



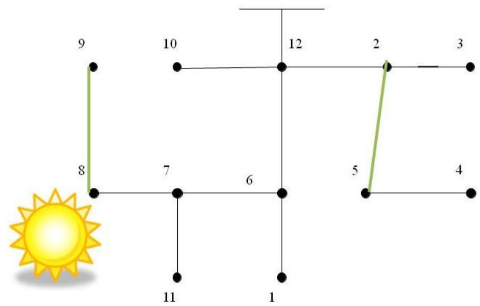
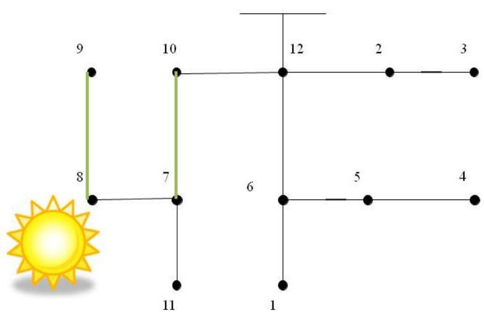


Figure 25. Configuration 9 **Figure 26. Configuration 10**



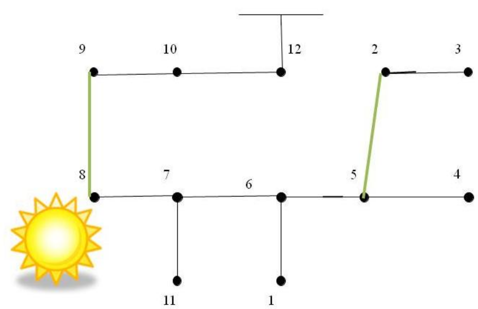
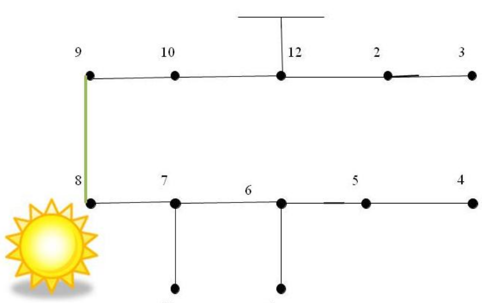


Figure 27. Configuration 11 **Figure 28. Configuration 12**



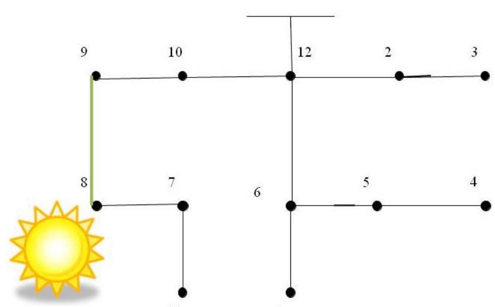


Figure 29. Configuration 13 **Figure 30. Configuration 14**

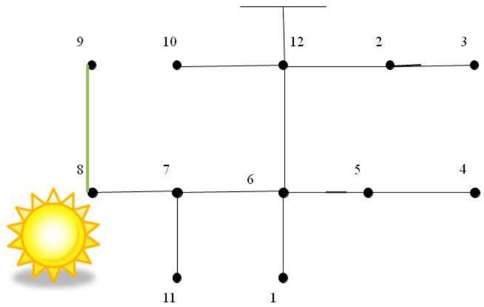


Figure 31. Configuration 15

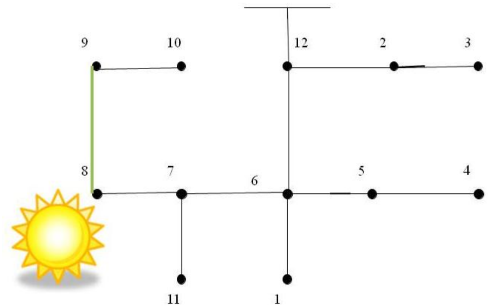


Figure 32. Configuration 16

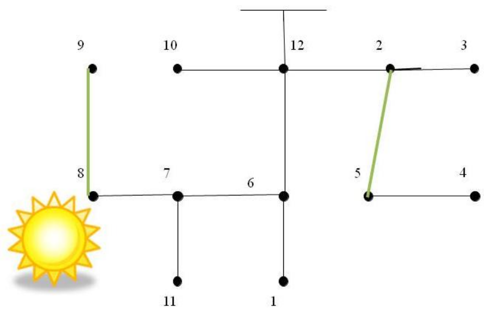


Figure 33. Configuration 17

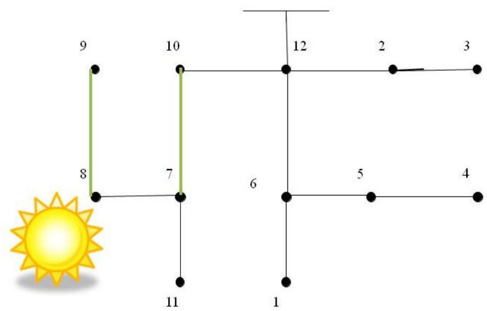


Figure 34. Configuration 18

11. Appendix B: Load Correlation Across the Network

It is important to show that the results of our model are robust given the assumption about distributing load across the different zones using correlated random variables. The first experiment we used to test this was to get real data from feeders in the Lisbon area for a 24-hour period. I normalized the loads by the average load in each feeder so that the demand would be small enough for our model. Since we only had a 24-hour period of data, we simulated adding wind to the model by looping through 365 days of scaled BPA wind using the same day of Lisbon feeder load. The results in Figure 35 show that the loss reductions predicted by BPA load at each interval fall within a standard deviation of loss reductions predicted by the Lisbon feeder load, and are only slightly higher than the mean.

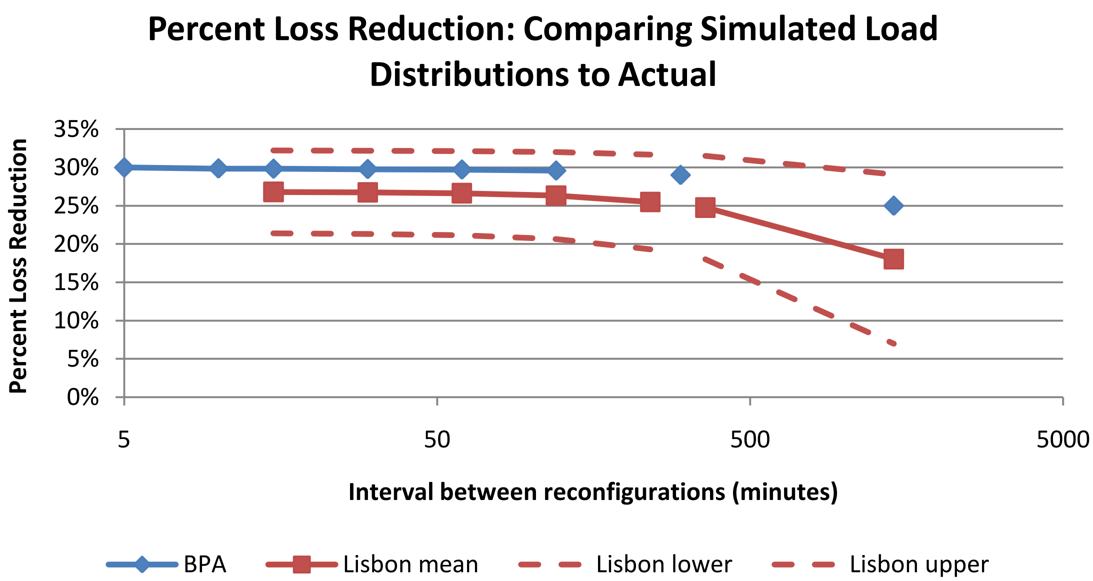


Figure 35. Percent Loss Reduction of BPA Load and Lisbon Feeder Load with BPA Wind

A second method I used to verify our assumption was to change the correlation of the random variables that determine the distribution of load across different zones. I bounded the calculation by using perfectly correlated and perfectly uncorrelated loads for each switching interval. The results in Figure 36 show that the base correlation (0.5) that I used and perfectly correlated loads behave almost identically; the no correlation scenario loss reductions drop off at large intervals, probably because the variability of the load makes it difficult for a single configuration to minimize losses over a long period of time.

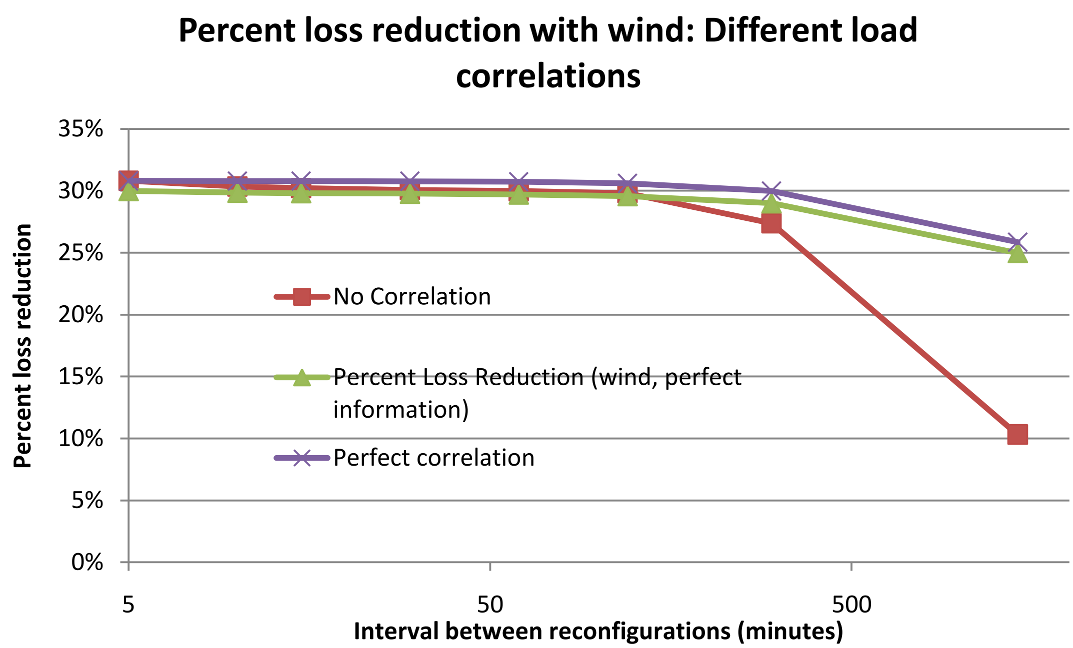


Figure 36. Percent Loss Reduction for Different Load Correlations, BPA Load and Wind Data

12. Appendix C: Model Line Characteristics

Table 7. Model line characteristics

Characteristic	**Value**
Base voltage	15 kV
Line length	0.65 km
Base current (1 pu)	385 A
Max current (1.17 pu)	450 A
Line impedance	0.25+0.35i ohms/km
Line admittance	0.7 kvar/km

[1] In the U.S., line switches called reclosers are used as circuit breakers to isolate faults, but we are not aware of any example of switches used to reduce operational losses. In the 1980s, Oak Ridge National Labs conducted an experiment on a distribution grid in Athens, TN that included reconfiguration. However, they did not experience significant loss reduction (Gnadt, 1990).

[2] Solar data (two years of data from the 5 MW Springerville Arizona array) comes from Tuscon Electric Power.

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[3] Convergence in this case refers to the calculation meeting the criteria that the difference in voltage for each node between two iterations does not exceed 0.0001.