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Did geomagnetic activity challenge electric power reliability during solar cycle 23? Evidence from the PJM regional transmission organization in North America

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[1] During solar cycle 22, a very intense geomagnetic storm on 13 March 1989 contributed to the collapse of the Hydro-Quebec power system in Canada. This event clearly demonstrated that geomagnetic storms have the potential to lead to blackouts. This paper addresses whether geomagnetic activity challenged power system reliability during solar cycle 23. Operations by PJM Interconnection, LLC (hereafter PJM), a regional transmission organization in North America, are examined over the period 1 April 2002 through 30 April 2004. During this time PJM coordinated the movement of wholesale electricity in all or parts of Delaware, Maryland, New Jersey, Ohio, Pennsylvania, Virginia, West Virginia, and the District of Columbia in the United States. We examine the relationship between a proxy of geomagnetically induced currents (GICs) and a metric of challenged reliability. In this study, GICs are proxied using magnetometer data from a geomagnetic observatory located just outside the PJM control area. The metric of challenged reliability is the incidence of out-of-economic-merit order dispatching due to adverse reactive power conditions. The statistical methods employed make it possible to disentangle the effects of GICs on power system operations from purely terrestrial factors. The results of the analysis indicate that geomagnetic activity can significantly increase the likelihood that the system operator will dispatch generating units based on system stability considerations rather than economic merit.

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1. Introduction

[2] During solar cycle 22, a very intense geomagnetic storm on 13 March 1989 led to the collapse of the Hydro-Quebec power system in Canada. This event clearly demonstrated that geomagnetic storms have the potential to lead to blackouts. This vulnerability exists because geomagnetically induced currents (GICs) can sharply degrade the performance of critical transmission infrastructure.

[3] No major blackouts were attributed to geomagnetic activity during solar cycle 23. However, this may understate the reliability challenge if system operators were able to avoid blackouts by undertaking actions that had nontrivial costs. The number of blackouts over a solar cycle may also be an unreliable metric of the potential reliability challenge if the vulnerability of the power grid is contingent on system conditions and the number of large geomagnetic storms is small.

[4] Indicative of space weather's perceived threat to the reliability of the electric power system, the North American Electric Reliability Corporation (NERC) has advised the electric power industry to monitor the power system for geomagnetic effects when the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) issues a *K*-index warning of *Kp* of 6 or higher [*Rollison et al.*, 2011]. The SWPC website indicates that this is approximately equivalent to a maximum change in the horizontal component of the geomagnetic field that

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equals or exceeds 120 nT/min (http://www.swpc.noaa.gov/info/Kindex.html). At the $Kp = 6$ level of geomagnetic activity, system operators are advised to increase reserves of reactive power, decrease loading on susceptible equipment, and consider increasing import capacity (see "Background for alert: Preparing for geo-magnetic disturbances," 2011, http://www.nerc.com/docs/pc/gmdtf/GMD_Background_Draft_05062011_CLEAN.pdf). More extensive measures are advised when more severe geomagnetic conditions are expected.

[5] This paper addresses whether geomagnetic activity was actually a challenge to power system reliability during solar cycle 23. Do the data support NERC's advisory or does the link between space weather and the power grid become an issue only when the magnitude of the geomagnetic storm reaches or exceeds that of March 1989?

[6] The paper uses data from the PJM regional transmission organization (RTO) in the mid-Atlantic region of the United States to examine the relationship between geomagnetically induced currents (GICs) and challenged power system reliability. This research follows *Forbes and St. Cyr* [2008], who presented evidence that various metrics of power grid operations in 12 geographically disparate electricity grids were statistically related with a proxy for GICs. More recently, *Forbes and St. Cyr* [2010] have presented multivariate statistical evidence that GICs contribute to constraints in PJM's 500 kilovolt (kV) transmission system.

[7] The remainder of the paper is organized as follows. Section 2 discusses reactive power, a form of power that is critical to the stability of the transmission system. It also discusses "reactive off-cost" operations, which are a set of procedures PJM implements when there are inadequate levels of reactive power. The incidence of these events is the metric of challenged reliability considered in this paper. Section 3 discusses the data employed in the study. Section 4 presents a chi-square analysis of the GIC proxy and the incidence of reactive off-cost events in the PJM transmission system. Section 5 presents a multivariate model of reactive off-cost events that takes into account possible confounding factors. Section 6 reports the estimation results and also offers evidence that the reactive power vulnerability of the transmission system is not constant over time but instead varies with power system conditions. Section 7 summarizes the findings and discusses research that could mitigate the overall reliability challenge by forecasting the vulnerability of the transmission system.

2. Reactive Power and the Reliability of the Power Grid

[8] PJM Interconnection coordinated the dispatch of 76,000 megawatts (MW) of generating capacity over approximately 32,000 km of transmission lines in all or parts of Delaware, Maryland, New Jersey, Ohio, Pennsylvania, Virginia, West Virginia, and the District of Columbia as of 30 April 2004. The sample period for this analysis is 1 April 2002 through 30 April 2004. During this period, PJM operated both real-time and day-ahead markets for energy. Prices in both markets are location-based, which means the prices will be equal across locations when the transmission system is uncongested but can vary substantially from one location to another when there are transmission constraints. For example, transmission constraints can lead to significant differences in the real-time price at PJM's Eastern Hub compared to its Western Hub.

[9] A substantial portion of PJM's generating capacity is accounted for by coal-fired power plants in the western part of the control area while demand centers are in the east. Exclusive of the environmental damage associated with coal-fired generation, the generating costs of producing electricity from coal are relatively low. Thus, market forces favor the dispatch of coal-fired electricity and the associated large transfers of electricity from the western portion of the control area to the eastern demand centers. For example, over the sample period, the average transfers of electricity at PJM's western interface were approximately 4800 megawatt hours (MWh) while the transfer limits, the values beyond which reactive and voltage criteria are violated, averaged approximately 5800 MWh. The averages of the transfers and the transfer limits at PJM's eastern interface were approximately 5000 and 6000 MWh, respectively. To put these values in perspective, based on data downloaded from the European Network of Transmission System Operators for Electricity (http://www.entsoe.net/home.aspx), the 2010 net transfer capacity of the transmission lines between France and Germany was approximately 2800 MWh for exports from France to Germany and 2850 for exports from Germany to France.

[10] High-voltage electricity transmission systems almost exclusively employ alternating current technology, with notable exceptions such as the interconnector between England and France, the cable that links the North and South Islands of New Zealand, and the Cross Sound cable project that links Long Island with Connecticut. For example, as of 31 December 2004, approximately 254,397 of the 258,634 km of high-voltage transmission lines (230 kV and above) in the United States were accounted for by alternating current technology [*North American Electric Reliability Corporation*, 2005]. In an alternating current system, voltage and current oscillate up and down 50 times per second in most of the world (60 times per second in North America). As a result, the power transmitted on single transmission line also pulsates up and down around the average value [*Sauer*, 2003]. This average value is a measure of "real" power. Another form of power known as reactive power is also supplied or consumed depending on whether current peaks before or after voltage [*U.S. Federal Energy Regulatory Commission (FERC)*, 2005]. Reactive power maintains the voltages required for system stability and thus is critical to the delivery of real power to consumers. Sources of reactive power include generators and capacitors. Reactive power is consumed by

transmission lines, transformers, and motors. Excessive reactive power consumption has the potential to lead to voltage collapse and system instability. A key attribute of reactive power is that its consumption can increase significantly with the distance transported [*FERC*, 2005]. This attribute is critical to the modeling of reactive power deficiencies.

[11] According to *FERC* [2005], voltage collapse due to inadequate reactive power has contributed to a number of blackouts. Among those cited by FERC were blackouts on 2 July 1996 and 10 August 1996 on the West Coast of the United States; 19 December 1978 in France; 23 July 1987 in Tokyo, Japan; 28 August 2003 in London, England; 23 September 2003 in Sweden and Denmark; and 28 September 2003 in Italy. FERC even notes that voltage collapse due to inadequate reactive power was a contributing factor to the blackout experienced by Hydro-Quebec on 13 March 1989.

[12] The U.S.-Canada Power System Outage Task Force investigated the causes of the 14 August 2003 blackout in the Northeast United States and Canada. The task force concluded that inadequate management of reactive power was a contributing factor in the blackout [*U.S.-Canada Power System Outage Task Force*, 2004, p. 18]:

> The Ohio phase of the August 14, 2003, blackout was caused by deficiencies in specific practices, equipment, and human decisions by various organizations that affected conditions and outcomes that afternoon—for example, insufficient reactive power was an issue in the blackout, but it was not a cause in itself. Rather, deficiencies in corporate policies, lack of adherence to industry policies, and inadequate management of reactive power and voltage caused the blackout, rather than the lack of reactive power.

[13] A 23 September 2003 article in the New York Times by Richard Pérez-Peña and Eric Lipton is somewhat more illuminating on the role of reactive power in the 14 August 2003 blackout [*Pérez-Peña and Lipton*, 2003, paragraph 5]:

> Experts now think that on Aug. 14, northern Ohio had a severe shortage of reactive power, which ultimately caused the power plant and transmission line failures that set the blackout in motion. Demand for reactive power was unusually high because of a large volume of long-distance transmissions streaming through Ohio to areas, including Canada, than needed to import power to meet local demand. But the supply of reactive power was low because some plants were out of service and, possibly, because other plants were not producing enough of it.

[14] PJM experienced significant reactive power/low voltage challenges in 1999. For example, very low voltages were recorded on the transmission system during a heat wave in July 1999 and all emergency procedures except for "manual load dump" were implemented [*PJM*, 2000, p. 4]. Voltages were low because the consumption of reactive power exceeded the supply [*PJM*, 2000]. One possible factor contributing to this imbalance was a lack of incentive for generators to produce reactive power since its production can reduce the quantity of real power that can be sold (see "Interim report of the U.S. Department of Energy's power outage study team," 2000, http://certs.lbl.gov/pdf/post-interim.pdf). A root-cause analysis gave rise to 20 recommendations. The first recommendation was the development of a comprehensive voltage operating criteria, with one stipulation that the criteria "should define limits associated with non-cost actions, off-cost actions, and load dump" [*PJM*, 2000, p. 11].

[15] With a number of important lessons learned from the July 1999 event and a new energy management system in place, PJM considers adherence to the reactive transfer limits at the internal interfaces within PJM (e.g., the eastern interface) to be critical to the reliability of its system. Its training materials note that "Small increase in flow or load can cause large voltage fluctuation" [*PJM*, 2008, p. 168] and that voltage collapse has potential to lead to a blackout of the system. In short, PJM reports that the "Reactive Transfer Limits are the *most critical* system reliability limits" because they represent the "largest potential system impact if exceeded" [*PJM*, 2008, p. 168]. It is therefore not surprising that an automated security analysis evaluates the transfer limits approximately every 5 min and that "PJM dispatchers continuously monitor and control the flow on each transfer interface so that the flows remain at or below the transfer limits" [*PJM*, 2011a, p. 45]. Those readers interested in learning more about PJM's views on reactive power are encouraged to read its reactive power factsheet [*PJM*, 2012a].

[16] PJM normally dispatches generators based on their cost, with the lowest cost generators being dispatched first. One major exception to this "economic merit," or "on-cost," method of dispatch is when generation is dispatched "out of economic merit order," or "off-cost," due to a transmission constraint [*PJM*, 2008, p. 8]. Adverse reactive power conditions can warrant a reduction in the transfer limits and thus can give rise to these events. PJM distinguishes this as a "reactive off-cost" operation, during which generators are redispatched so that the transmission flows at the internal interfaces remain at or below the reactive transfer limits.

[17] Given that the cost of generation is a lower priority during a reactive off-cost operation, it is reasonable to suppose that these events would have a market impact. Consistent with this view, the average real-time price at PJM's Eastern Hub over the sample period was about \$0.70 per MWh higher than at its Western Hub when the transmission system was in reactive on-cost status. When reactive off-cost operations were in effect, the average real-time price at the Eastern Hub was approximately \$11.36 per MWh higher than at the Western Hub. This represents an approximately 20% premium above the average day-ahead price at PJM's Eastern Hub for those same market periods. This is obviously a significant market impact. However, the apparent market impact is surely modest relative to the costs imposed on consumers should a reactive off-cost operation not be declared and the system collapses as a result.

[18] With respect to space weather, *Kappenman* [2003] has pointed out that there is an increase in reactive power consumption when GICs pass through a transformer. In his words [*Kappenman*, 2003, p. 4]:

> Though these quasi-DC currents are small compared to the normal AC current flows in the network, they have very large impacts upon the operation of transformers in the network…. The principal concern to network reliability is due to increased reactive power demands from transformers that can cause voltage regulation problems, a situation that can rapidly escalate into a grid-wide voltage collapse.

[19] Consistent with this emphasis on GICs, reactive power consumption, and the challenge to system stability, *Kappenman* [2010, Figures 2–7] has presented evidence that GICs increased reactive power consumption in Hydro-Quebec on 13 March 1989 by a factor of approximately 8 over the course of approximately 6 min. Power consumption increased from approximately 200 megavolt ampere reactive (MVAR) to about 1600 MVAR just minutes prior to the "tripping" of the five 735 kV tie lines needed to ensure electricity transfers to Montreal from the remote hydro generation facilities at James Bay [*Kappenman*, 2010]. Hydro-Quebec was unable to make up the loss in transmission, and the system collapsed. In summary, the Hydro-Quebec system collapsed on 13 March 1989 because of GIC-induced consumption of reactive power.

[20] Other researchers also have noted the impact of GICs on reactive power demands. For example, *Molinski* [2002] cites evidence of a linear relationship between GIC levels and the reactive power consumption by high-voltage transformers. According to Molinski, this relationship is evident even at low GIC levels [*Molinski*, 2002, Figure 9].

[21] PJM recognizes the challenge to reliability posed by space weather. In its words, "Geomagnetically-induced currents (GIC) caused by the solar magnetic disturbance (SMD) flow through the power system equipment and facilities may result in major increases in system reactive requirements, equipment damage, and disruption of interconnected system operation." [*PJM*, 2012c, p. 46]. To avoid these effects, PJM invokes its SMD conservative operations procedures. These operations are put into effect based on ground current readings by PJM. During these events, operators curtail transmission and generators are dispatched on the basis of system stability considerations, not economics. According to PJM's emergency operations manual, "Upon identification of a geomagnetic disturbance, PJM dispatcher operates the system to geomagnetic disturbance transfer limits" [*PJM*, 2012c, p. 46]. PJM makes it clear that the imposition of these limits has implications for power generation [*PJM*, 2012c, p. 47]:

> When the GIC limit is approached or exceeded, generation redispatch assignments are made in the most effective areas to control this limit. PJM dispatcher also evaluates the impact of the existing inter-area transfers and modifies the schedules that adversely affect the GIC transfer limit.

PJM details its views on solar magnetic disturbances, i.e., space weather, in its solar magnetic disturbances factsheet [*PJM*, 2012b].

[22] PJM declared its SMD procedures during the Bastille Day storm in July 2000. Specifically, the procedures were implemented over the time period 15:30–21:07 LT on 15 July 2000. Interestingly, PJM's raw data files (available at http://pjm.com/markets-and-operations/ops-analysis/offcostop.aspx) refer to this event as "reactive (SMD)" in nature. Both the transfer limits and flows were curtailed during this event. Problematically in terms of system reliability, the average transfers at PJM's eastern interface exceeded the limit during 1 h.

[23] PJM replaced its emergency reporting system since 2000 with the result being that the current system does not reflect the July 2000 SMD event. However, the current reporting system does reveal that conservative operations in response to solar magnetic disturbances were declared on four occasions over the sample period corresponding to this study (http://www.pjm.com/markets-and-operations/etools/emerg-procedure.aspx). All of these instances occurred in October and November 2003. These actions are consistent with the NOAA SWPC assessment of the October–November 2003 storms (http://www.nws.noaa.gov/os/assessments/pdfs/SWstorms_assessment.pdf).

[24] There was an abnormally high incidence of reactive off-cost operations in PJM during the Halloween storms of 2003. Specifically, from 29 to 31 October 2003, reactive off-cost operations were implemented in 18 of the 72 h, a rate more than twice the average rate of incidence. Some coincided with PJM's implementation of its SMD conservative operations but others did not. During these same storms the Swedish high-voltage power transmission system also experienced problems [*Pulkkinen et al.*, 2005]. *Forbes and St. Cyr* [2008] also noted a series of emergency deployments of balancing power in the Netherlands power grid during these same storms and presented evidence that the incidence of the emergency deployments is statistically related to the value of a GIC proxy. Specifically, based on 3 years of quarterly hour data, they report a p-value of 3.082×10^{-14} (a value corresponding to the odds of flipping a fair coin approximately 45 times and observing a "heads" each time). The null hypothesis of no relationship was therefore rejected.

3. Data

[25] A number of factors can give rise to off-cost operations. For example, PJM has indicated that an off-cost operation is the most common response to violations of the thermal transmission limits [*PJM*, 2008]. This study focuses exclusively on reactive off-cost operations. The time periods in which off-cost operations were implemented are posted on the PJM website (http://pjm.com/markets-and-operations/ops-analysis/offcostop.aspx). The raw data indicate whether the root cause of an off-cost operation was "reactive" in nature. As discussed in the previous section, PJM is able to identify the root cause

because it monitors reactive conditions at several interfaces within its system [*PJM*, 2011a]. On the basis of these readings, all or a portion of the system is operated reactive on-cost or off-cost. The raw data representing reactive off-cost events were downloaded and a binary variable was created with 1 representing the outcome when all or a portion of the system was operated reactive off-cost for all or part of an hour and zero otherwise.

[26] Following *Forbes and St. Cyr* [2010], we dropped observations from the sample if geomagnetic data were missing, data on forecasted load were missing for any hour of the day, or if ambient temperature data were missing. The sample also excludes transition days between standard and daylight saving time. The hours corresponding to the August 2003 Northeast blackout were also excluded from the analysis. In total, 2,001 deletions left a sample of 16,262 observations to be analyzed. Over the sample period, one or more reactive off-cost operations were in effect during 1727 h, about 10% of the sample. In 476 of these periods, PJM also experienced constraints in its 500 kV transformers, the incidence of which has been analyzed by *Forbes and St. Cyr* [2010].

[27] Data on hourly load and the locational prices by hour were downloaded directly from the PJM web site. The day-ahead hourly forecasted load data was obtained from the Itron Corporation (www.itron.com). The hourly ambient temperature data were obtained from the National Weather Service for the Baltimore-Washington, Pittsburgh, and Philadelphia airports. Data from these airports yielded significantly fewer missing values compared to the alternatives.

[28] The econometric results reported in section 6 make use of day-ahead electricity price data weighted by the prices of coal and natural gas, the primary fossil fuels used by generators in PJM. These variables are included because they reflect expected operating conditions. Specifically, they proxy the opportunity costs of generators of providing reactive power. Economic dispatch in PJM is based on offers to provide generation, which, in turn, are based on marginal costs. In the absence of transmission constraints, the offers are accepted beginning with the lowest-priced offers. Higher-priced offers are then accepted until the total amount of generation offered equals the anticipated demand for electricity. The day-ahead price is determined by the expected operating characteristics of the last generating unit that is dispatched. The day-ahead price of electricity relative to the price of the fuels used to generate the electricity therefore reflects expected operating conditions as well as the opportunity cost of providing reactive power. We obtained natural gas price data from NGI Intelligence Press (http://intelligencepress.com); we obtained coal price data from Platts (http://www.platts.com). We transformed prices into U.S. dollars per GJ. The median values of the ratios are approximately 6.6 and 25.2 for natural gas and coal, respectively. When adverse operating conditions are expected, the price ratio for natural gas can exceed 50, while the ratio for coal can exceed 150.

[29] PJM has significant nuclear generation capacity and thus some may wonder why the price ratios discussed above do not include nuclear generation. The economic reality is that nuclear power generating units have very low marginal costs and a nuclear plant is highly unlikely to be the marginal generating unit. Consistent with this view, the 2006 PJM State of the market report [*PJM*, 2007] indicated that nuclear was *never* the marginal fuel during the period 2004–2006 (data before 2004 are unavailable). In contrast, coal and natural gas were the marginal fuels in more than 90% of the operating periods.

[30] Previous literature has indicated that GIC levels in power grids are closely related to the time derivative of the horizontal component of the geomagnetic field [*Bolduc et al.*, 1998; *Coles et al.*, 1992; *Mäkinen*, 1993; *Viljanen*, 1998; *Viljanen et al.*, 2001]. Accordingly, GICs in this study are proxied by the time derivative of the horizontal component (dH/dt) of the geomagnetic field.

[31] For each 1-h market period, the rate of the change in the horizontal component of the geomagnetic field (dH/dt) was calculated using the largest change (in absolute value) in the 1-min values of horizontal component of the geomagnetic field over the hour in question.

[32] The raw data were downloaded from the Intermagnet website (http://www.intermagnet.org). Specifically, the study uses data reported by the U.S. Geological Survey's geomagnetic observatory in Fredericksburg (FRD), Virginia, which is located about 75 km south of the boundaries of the PJM control area during the study period. The peak value of dH/dt over the sample period was 178.4 nT/min. Based on 1-min FRD data downloaded from the World Data Centre for Geomagnetism, Edinburgh (http://www.wdc.bgs.ac.uk/catalog/master.html), this peak value was significantly lower than the peak of 353 nT/min that was obtained for FRD during the 13 March 1989 geomagnetic storm that crashed the Hydro-Quebec power system.

4. Preliminary Analysis Using a Nonparametric Test Statistic

[33] Following *Forbes and St. Cyr* [2008, 2010], this study initially tests the hypothesis that GIC levels and the incidence of reactive off-cost events are related using Pearson's chi-square statistic, a nonparametric test statistic that makes no assumption about the distribution of the frequencies. In contrast to simple correlation analysis, it does not presume that the relationship is linear.

[34] Following *Sheskin* [2007], we proceed by first establishing a number of mutually exclusive categories for the GIC proxy. The GIC proxy data were categorized by quartile where GIC1, GIC2, GIC4, and GIC4 represent the first through the fourth quartiles, respectively. With respect to grid conditions, we will consider two categories: reactive off-cost (Off-Cost) and reactive on-cost (On-Cost).

[35] The chi-square analysis proceeds by constructing a cross-tabulation between the measure of grid conditions and the GIC proxy and reporting on the observed

Table 1. Observed Frequencies for the Categories Representing GICs and Reactive Conditions in the PJM Power Grid, 1 April 2002–30 April 2004

	On-Cost	Off-Cost
GIC1	3819	298
GIC2	3905	417
GIC3	3506	483
GIC4	3305	529

frequency in each cell (Table 1). This observed frequency is then compared to the frequency that would be expected if the two variables were statistically independent (Table 2). The procedure for calculating these values is presented in *Forbes and St. Cyr* [2010]. Table 3 presents the ratio of observed to expected frequencies. Consistent with the hypothesis that there is a causal relationship between GIC levels and the incidence of reactive off-cost operations, the reader should observe that the ratio corresponding to off-cost (on-cost) monotonically increases (declines) as the GIC category increases (decreases). For example, the observed ratio associated with GIC1 ∩ off-cost is about 32% lower than expected while the observed ratio associated with GIC4 ∩ off-cost is about 30% higher than what would be expected under the null hypothesis of statistical independence.

[36] The chi-square test can be used to assess whether the reported differences between the observed and expected frequencies are statistically significant. The chi-square test statistic is calculated as follows:

$$\chi = \sum_{i=1}^{R}\sum_{j=1}^{C}\frac{\left(f_{i,j}^{o} - f_{i,j}^{e}\right)^{2}}{f_{i,j}^{e}}, \tag{1}$$

where $f_{i,j}^{o}$ represents the observed frequency, $f_{i,j}^{e}$ represents the expected frequency under the assumption that the null hypothesis is true, R is the number of row categories, and C is the number of column categories.

[37] The null hypothesis of statistical independence is rejected if the calculated chi-square statistic exceeds $(\chi^2)^*$, the critical value of the statistic corresponding to the level of statistical significance. The exact value of $(\chi^2)^*$ will depend on the number of degrees of freedom that will equal the number of row categories minus one multiplied by the number of column categories. In this case there are four GIC categories and two power grid categories; thus there are three degrees of freedom. The corresponding critical value of the chi-square statistic at the 1% level of statistical significance equals 11.345. In this case, the calculated chi-square statistic equals 103.994, which exceeds the critical value of the statistic by a substantial margin. The associated *p*-value equals 2.151E-22. This value is approximately equal to the probability of flipping a fair coin 72 times and observing a "head" on each flip. Most individuals who flip a coin that is claimed to be "fair" 72 times and observe a "head" each and every time would most likely conclude that the coin is not fair. In any event, the *p*-value in this case is well below 0.01 and thus the null hypothesis of statistical independence between the GIC proxy and the incidence of reactive off-cost events is rejected at the 1% level of statistical significance. This finding does not "prove" that GICs contribute to the implementation of reactive off-cost events, but it is nevertheless consistent with a causal relationship. In the next section, we explore this issue more rigorously taking into account that there are other possible drivers of these events.

Table 2. Expected Frequencies Under the Assumption of Statistical Independence for the Categories Representing GICs and Conditions in the PJM Power Grid, 1 April 2002–30 April 2004

	On-Cost	Off-Cost
GIC1	3680	437
GIC2	3863	459
GIC3	3565	424
GIC4	3427	407

Table 3. The Ratio of Observed to Expected Frequencies for the Categories Representing GICs and Conditions in the PJM Power Grid, 1 April 2002–30 April 2004

	On-Cost	Off-Cost
GIC1	1.038	0.682
GIC2	1.011	0.909
GIC3	0.983	1.140
GIC4	0.964	1.299

5. A Multivariate Model of Reactive Off-Cost Events

[38] In this section of the paper, we examine the relationship between the GIC proxy and the metric of challenged reliability using the multivariate logit model specification commonly used by researchers in making statistical inferences with respect to the incidence of binary events. This specification is similar to the probit methodology employed by *Forbes and St. Cyr* [2010] in that the two methodologies yield similar probabilities in most cases [*Greene*, 2008]. One advantage of the logit specification relative to the probit is that the transformed estimated coefficients are easier to interpret. Specifically, the predicted value of the dependent variable is the odds ratio, p/(1-p), where *p* is the probability of the binary dependent variable being equal to one. Each exponentiated coefficient represents the estimated change in the odds ratio corresponding to a one-unit increase in the corresponding predictor variable holding other variables constant. The dependent variable in the analysis is a binary variable whose value equals one if a reactive off-cost action by the system operator occurs in hour t and equals zero otherwise. The explanatory variable of interest in this case is the GIC proxy (GIC), and thus its exponentiated

coefficient represents the estimated effect of a 1-unit increase in the GIC proxy on the odds of an off-cost event, all other factors being held constant. To control for possibly confounding factors, the model includes explanatory variables that are presumed to directly affect or proxy the factors that affect the probability of a reactive off-cost event. Exclusive of ambient temperature, scheduled electricity flows with other control areas and the level of actual load, the control variables are largely based on the findings of *Forbes and Zampelli* [2011], who present an analysis of load forecasting errors; load-forecasting errors being just another form of the energy imbalances examined in this study. Their analysis presented one year of out-of-sample evidence for the California Independent System Operator. The analysis indicated that the root-mean squared error of the day-ahead load forecast for the northern portion of the control area can be reduced by about 23% if the load forecasts are revised. Such revision would be based on various measures of the day-ahead load forecast and outcomes in the day-ahead electricity market. Each of these factors is discussed below.

5.1. Ambient Temperature

[39] We hypothesize that the probability of a reactive off-cost operation is higher, the higher the ambient temperature (T). This is consistent with the findings of *Forbes and St. Cyr's* [2010] analysis of transformer constraints in PJM's 500 kV transmission system.

5.2. Actual Load, Forecasted Load, and the Intraday Variability in Forecasted Load

[40] We hypothesize that the probability of an off-cost operation is higher the higher the level of both actual load (AL) and forecasted load (FL), all other factors being held constant. The rationale for this hypothesis is that reactive power is consumed by transmission lines and transformers, which are more heavily utilized when load is higher. It is further hypothesized that the probability of a reactive off-cost operation is lower the higher the intraday variability in forecasted load as measured by the coefficient of variation (CVFL). The rationale for this hypothesis is that a high degree of variability in the hourly forecasted load can be expected to favor the scheduled dispatch of more flexible generating units relative to base load units. This may have implications for the geographic distribution of generation relative to load, which in turn may have reactive power ramifications. The skewness in the intraday forecasted load is also hypothesized to be a useful predictor. Positive skewness is represented by PSFL which equals the skewness in the hourly forecasted load for each day when the skewness is positive. It is equal to zero otherwise. The variable NSFL equals the absolute value of the skewness in the hourly forecasted load for each day corresponding to hour t when the skewness in the forecasted load is negative. It is equal to zero otherwise. We hypothesize that the probability of an off-cost operation is higher the higher the absolute value of this measure. The rationale for this hypothesis is that insufficient levels of reactive power may be more likely on those days when there are several hours of unusually low levels of power generation.

5.3. Scheduled Imports and Exports

[41] The variable SI represents scheduled net imports during those hours in which PJM was a net importer. It is equal to zero otherwise. We hypothesize that higher reliance on imports increases the probability that a reactive off-cost operation will be implemented. The rationale for this hypothesis is that imports represent electricity flows that consume reactive power without the generation that supplies reactive power. The variable SE represents scheduled net exports during those hours in which PJM was a scheduled net exporter. It is equal to zero otherwise. We hypothesize that increases in net scheduled exports reduces the probability that PJM would implement a reactive off-cost operation.

5.4. The Day-Ahead Electricity Price Relative to Fuel Costs

[42] Coal and natural gas are the primary fossil fuels used to produce electricity in PJM. The model employs the variable DPG, defined as the ratio of the hourly day-ahead system price of electricity relative to the price of natural gas. The model also uses the variable DPC, which is the hourly day-ahead system price of electricity relative to the price of coal. Following from economic theory, we hypothesize that these day-ahead price ratios are useful proxies for expected operating conditions. *Forbes and Zampelli* [2011] have presented evidence on this point. We also hypothesize that the probability of an off-cost operation is higher, the higher these day-ahead price ratios.

5.5. Relative Fuel Prices

[43] Generating plants in PJM that utilize coal to produce electricity tend to be located greater distances from demand centers as compared to plants that produce electricity using natural gas. Under on-cost conditions, generators are dispatched based on costs which are significantly determined by fuel prices. Thus, because reactive power does not travel well, changes in the price of natural gas relative to coal may have implications for the incidence of reactive off-cost events. To account for this, the model includes the ratio of the natural gas price relative to the coal price (PGC) as an explanatory variable.

5.6. The Intraday Variability in the Day-Ahead Prices

[44] We hypothesize that the probability of a reactive off-cost operation is higher, the higher the coefficient of variation in the day-ahead hourly prices (CVDP). The rationale for this hypothesis is that the coefficient of variation in the hourly prices may be a useful predictor of operational uncertainty.

[45] It is also hypothesized that the probability of a reactive off-cost event is influenced by the degree of skewness in the intraday prices. When prices are negatively skewed, generators with limited flexibility in terms

of output (e.g., nuclear) may overproduce relative to the scheduled level during the periods of low prices to ensure the ability to meet demand in the lucrative peak load periods. When prices are positively skewed, the modal price may be insufficient to justify economically full adherence to the generation schedule. Because generation is a source of reactive power, we hypothesize that that odds of a shortfall in reactive power, i.e., the odds of a reactive off-cost event, is lower (higher), the higher the negative (positive) skewness in the hourly prices. The degree of skewness is represented by the variables *PSDP* and *NSDP*. *PSDP* equals the skewness in the hourly day-ahead prices for each day when the skewness in the hourly prices is positive. It is equal to zero otherwise. *NSDP* equals the absolute value of the skewness in the hourly day-ahead prices for each day when the skewness in the hourly prices is negative. It is equal to zero otherwise.

5.7. Known Transmission Constraints

[46] Following *Forbes and St. Cyr* [2010], known transmission constraints can be measured by the absolute value of the difference in the day-ahead hourly prices between PJM's Eastern and Western hubs (DCC). We hypothesize that the probability of an off-cost operation is higher, the higher this day-ahead measure of congestion costs.

5.8. Other Factors

[47] Other factors can influence the probability of a reactive off-cost event. To capture the influence of unobserved hour-of-the-day effects, this study employs binary variables to represent each hour of the day (H_k where k = 2, 3, 4 … 24) exclusive of hour 1, the effect of which is reflected in the overall constant term. Having hour 1 be reflected in the constant term avoids the problem of singularity in the matrix used to generate the estimates. Unobserved hour-of-the-day effects are controlled for by binary variables to represent each day of the week (D_j where j = 1, 3, 4, 5, 6, 7), exclusive of Monday, the effect of which is reflected in the overall constant term. Reflecting one of the days of the week in the constant term avoids the problem of singularity in the matrix used to generate the estimates.

[48] In its most general form, the model is given by:

$$p = f(D_j, H_k, T, FL, CVFL, PSFL, NSFL, SI, SE, DPG, DPC, PGC, CVDP, PSDP, NSDP, DCC, GIC), \quad (2)$$

where p is the probability of a reactive off-cost event.

[49] The estimation of (2) was conducted using the logit formulation supplemented by the multivariable fractional polynomial (MFP) modeling approach. This technique is useful when one suspects that some or all of the relationships between the dependent variable and the explanatory variables are nonlinear [*Royston and Sauerbrei*, 2008] but there is little or no basis, theoretical or otherwise, on which to select a particular functional form. The MFP approach begins by estimating a model that is strictly linear in the explanatory variables. Subsequent estimations then cycle through a battery of nonlinear transformations of the explanatory variables (positive and negative powers, natural logarithms, etc.) until it obtains the specification that best predicts the dependent variable. In our case, the analysis provided support for including 11 of the explanatory variables with powers other than unity. The variables in question are *T*, *FL*, *CVFL*, *NSFL*, *AL*, *SI*, *DPC*, *DPG*, *PSDP*, *NSDP*, and *DCC*. In the case of temperature, the MFP suggested specification is $\ln(T + 15)$, where 15 is the constant needed to avoid taking the logarithm of a negative value. For the variable *PSDP*, the specification is $\ln(PSDP + 0.001)$, where 0.001 is a constant needed to avoid taking the logarithm of zero. All the other MFP specifications involve the exponents −2, 0.5, and 3. For example, the MFP specified formulations for the variable *AL* is cubic.

[50] The logit/MFP estimating equation is:

$$\begin{aligned} Ln(p/(1-p)) = {} & c + \sum_{k=2}^{7}\gamma_k D_k + \sum_{j=2}^{24}\beta_j H_j + \alpha_1 \ln(T+15) + \alpha_2 FL \\ & + \alpha_3 CVFL^3 + \alpha_4 PSFL + \alpha_5 NSFL^3 + \alpha_6 AL^3 \\ & + \alpha_7 SI^{0.5} + \alpha_8 SE + \alpha_9 DPC^{-2} + \alpha_{10} DPG^3 \\ & + \alpha_{11} PGC^{-2} + \alpha_{12} CVDP + \alpha_{13} \ln(PSDP + .001) \\ & + \alpha_{14} NSDP^3 + \alpha_{15} DCC^{0.5} + \delta GIC. \end{aligned} \quad (3)$$

The transformation on the left-hand side of (3), the logit, takes a number that is restricted to the [0, 1] interval and converts it into a value that has no upper or lower bound. Consequently, even when the all the explanatory variables have unitary exponents, the estimating equation is nonlinear, with the marginal impact of any single independent variable contingent on the values of the others. In contrast, under the more familiar ordinary least squares specification the probability that the action will occur is simply a linear function of the independent variables with no interaction effects. It is also possible that the ordinary least squares specification could yield a predicted probability that is negative, a result that is obviously nonsensical [*Greene*, 2008].

6. Estimation and Results

[51] There is the possibility that the effect of GICs on the probability of a reactive off-cost event is subject to a threshold. To assess this model specification issue, equation (3) was estimated 101 times with an assumed GIC threshold alternatively assumed to be 0, 1, 2, 3 … 100 nT/min. Based on the resulting values of the McFadden R-squared there is no evidence of a positive threshold. Specifically, the value of the McFadden R-squared was maximized when a threshold of zero was assumed.

[52] Table 4 presents the estimation results. The coefficient on the GIC variable indicates that the coefficient is positive as hypothesized and is also statistically significant at the 1% level as evidenced by its *p*-value of less than

Table 4. Estimation Results for Equation (3)

Variable	Coefficient	Estimated Coefficient	Exponentiated Estimated Coefficient	T Statistic	P-Value
Constant	C	−8.066	3.14E-04	−11.82	<0.001
Hour 2	β_2	0.107	1.113	0.36	0.721
Hour 3	β_3	−0.025	0.975	−0.08	0.94
Hour 4	β	0.086	1.090	0.26	0.795
Hour 5	β_5	0.017	1.017	0.05	0.958
Hour 6	β_6	−0.101	0.904	−0.35	0.727
Hour 7	β_7	−0.483	0.617	−1.77	0.076
Hour 8	β_8	−0.634	0.530	−2.42	0.015
Hour 9	β_9	−0.470	0.625	−1.88	0.06
Hour 10	β_{10}	−0.537	0.584	−2.19	0.029
Hour 11	β_{11}	−0.509	0.601	−2.12	0.034
Hour 12	β_{12}	−0.519	0.595	−2.16	0.031
Hour 13	β_{13}	−0.614	0.541	−2.53	0.012
Hour 14	β_{14}	−0.726	0.484	−2.93	0.003
Hour 15	β_{15}	−0.750	0.472	−3	0.003
Hour 16	β_{16}	−0.716	0.488	−2.88	0.004
Hour 17	β_{17}	−0.611	0.543	−2.47	0.013
Hour 18	β_{18}	−0.597	0.550	−2.47	0.014
Hour 19	β_{19}	−0.699	0.497	−2.9	0.004
Hour 20	β_{20}	−0.805	0.447	−3.36	0.001
Hour 21	β_{21}	−0.822	0.439	−3.39	0.001
Hour 22	β_{22}	−0.581	0.559	−2.41	0.016
Hour 23	β_{23}	−0.263	0.769	−1.08	0.281
Hour 24	β_{24}	−0.028	0.972	−0.11	0.914
Sunday	γ_1	0.001	1.001	0	0.997
Tuesday	γ_2	−0.373	0.688	−3.37	0.001
Wednesday	γ_3	−0.249	0.780	−2.3	0.021
Thursday	γ_4	−0.376	0.687	−3.33	0.001
Friday	γ_5	−0.297	0.743	−2.68	0.007
Saturday	γ_6	−0.161	0.851	−1.04	0.298
Ln(T + 15)	α_1	1.611	5.009	12.71	<0.001
FL	α_2	2.22E-05	1.000	1.25	0.21
CVFL^3	α_3	−307.266	0.000	−9	<0.001
PSKFL	α_4	−3.706	0.025	−2.58	0.01
NSKFL^3	α_5	1.721	5.592	6.57	<0.001
AL^3	α_6	2.65E-14	1.000	7.32	<0.001
$\mathrm{SI.}^5$	α_7	0.029	1.029	6.8	<0.001
SE	α_8	−0.002	0.998	−1.07	0.283
DPC^{-2}	α_9	−23.329	7.4E-11	−8.69	<0.001
DPG^3	α_{10}	0.001	1.001	3.53	<0.001
PGC^{-2}	α_{11}	−13.463	1.42E-06	−11.18	<0.001
CVDP	α_{12}	4.743	114.831	5.77	<0.001
PSDP^3	α_{13}	0.061	1.063	4.6	<0.001
NSDP^3	α_{14}	−1.133	0.322	−3.35	0.001
$\mathrm{DCC}^{.5}$	α_{15}	0.123	1.131	5.4	<0.001
GIC	δ	0.018	1.019	3.4	0.001
Number of observations	16262				
Number of positive observations	1727				
McFadden's R^2	0.211				
Percentage of correct reactive off-cost status predictions	70				
Percentage of correct reactive on-cost status predictions	91				
Log likelihood full model	−4342.9228				
Log likelihood intercept only	−5504.570				

0.01. In terms of magnitude, the exponentiated estimated coefficient indicates that holding other factors constant, a 1-unit increase in the GIC proxy increases the odds ratio of a reactive off-cost event by 1.

[53] With respect to the other independent variables, the coefficients on the binary variables indicate that reactive off-cost events are less likely during periods of known peak generation. For example, the coefficients corresponding to the variables Friday and hour 17 are negative and statistically significant at the 5% level as evidenced by their p-values being less than 0.05. The signs of estimated coefficients corresponding to $\mathrm{Ln}(T + 15)$, FL, AL, and $CVFL^3$

Table 5. A Listing of 50 Market Periods in Which the Probability of a Reactive Off-Cost Event Was Significantly Elevated by Space Weather[a]

Day	Month	Year	Hour (UT)	Predicted Probability of Off-Cost Operations	Predicted Incremental GIC-Associated Probability of Off-Cost Operations	Predicted Probability of Off-Cost Operations in the Absence of Space Weather	dH/dt (nT/min)	Comment
30	10	2003	19	0.746	0.647	0.100	178.4	
29	10	2003	14	0.722	0.600	0.122	159	PJM's solar magnetic disturbance procedures were implemented
31	10	2003	0	0.607	0.459	0.148	118.8	
31	10	2003	2	0.493	0.411	0.082	129.9	
29	10	2003	18	0.437	0.340	0.097	107.5	PJM's solar magnetic disturbance procedures were implemented
29	10	2003	16	0.472	0.338	0.134	95.3	PJM's solar magnetic disturbance procedures were implemented
29	10	2003	17	0.455	0.338	0.117	99.9	PJM's solar magnetic disturbance procedures were implemented
30	10	2003	21	0.465	0.295	0.170	78.6	
30	10	2003	22	0.522	0.291	0.231	70.2	
30	10	2003	20	0.339	0.247	0.092	88.4	
30	10	2003	23	0.416	0.245	0.171	67.4	
31	10	2003	12	0.304	0.232	0.072	93.7	
30	10	2003	1	0.308	0.212	0.096	77.7	
29	10	2003	15	0.327	0.189	0.138	60.3	
29	10	2003	13	0.280	0.156	0.123	55.2	
30	10	2003	0	0.282	0.153	0.128	53.2	
29	10	2003	19	0.238	0.152	0.086	65.4	
24	10	2003	22	0.337	0.148	0.189	42.4	
29	10	2003	12	0.233	0.139	0.093	58.7	
29	10	2003	21	0.268	0.137	0.131	48.3	
23	5	2002	15	0.196	0.126	0.070	64.1	
1	8	2002	23	0.838	0.123	0.715	39.4	
29	10	2003	20	0.196	0.119	0.078	58	
18	8	2002	18	0.902	0.105	0.796	46.4	
24	10	2003	15	0.288	0.102	0.187	30.9	
29	5	2003	19	0.156	0.099	0.057	60.6	
24	10	2003	21	0.263	0.094	0.168	30.7	
17	4	2002	16	0.718	0.093	0.625	23.1	
17	4	2002	15	0.630	0.091	0.539	20.5	
31	10	2003	11	0.154	0.087	0.067	50.9	
29	10	2003	22	0.288	0.087	0.201	25.7	
31	10	2003	13	0.177	0.083	0.094	39.8	
17	4	2002	18	0.809	0.083	0.727	25.4	
15	7	2002	20	0.418	0.082	0.336	19.1	
17	7	2002	16	0.338	0.082	0.256	21.4	
31	10	2003	1	0.159	0.069	0.090	35.4	
22	1	2004	1	0.177	0.069	0.109	30.9	
30	5	2003	20	0.211	0.068	0.143	25.6	
30	10	2003	18	0.180	0.065	0.115	28.5	
29	10	2003	11	0.132	0.064	0.068	39.8	
30	10	2003	16	0.191	0.061	0.129	25.1	
29	5	2003	22	0.103	0.061	0.042	52.5	
20	11	2003	13	0.108	0.061	0.047	48.6	
23	5	2002	16	0.129	0.060	0.069	37.8	
29	5	2003	20	0.117	0.056	0.061	38.6	
29	10	2003	6	0.067	0.056	0.011	99.3	
29	8	2003	20	0.695	0.055	0.639	13.6	
9	9	2003	20	0.207	0.055	0.152	20.4	
29	10	2003	23	0.238	0.054	0.184	17.7	
22	1	2004	13	0.228	0.054	0.175	18.3	

[a] Because of independent rounding, the predicted probability in the seventh column plus the predicted incremental probability do not add up to equal the predicted probability in the fifth column.

Table 6. A Listing of 50 Market Periods in Which the Probability of a Reactive Off-Cost Event Was Not Significantly Elevated by Space Weather[a]

Day	Month	Year	Hour (UT)	Predicted Probability of Off-Cost Operations	Predicted Incremental GIC-Associated Probability of Off-Cost Operations	Predicted Probability of Off-Cost Operations in the Absence of Space Weather	dH/dt (nT/min)
30	7	2002	20	0.9999	7.57E-06	0.9998	2.8
30	7	2002	19	0.9998	7.33E-06	0.9998	2.3
30	7	2002	18	0.9997	1.01E-05	0.9997	2
14	8	2002	19	0.9996	9.60E-06	0.9996	1.4
30	7	2002	21	0.9996	2.03E-05	0.9996	2.6
5	8	2002	20	0.9996	1.13E-05	0.9996	1.4
14	8	2002	20	0.9981	5.03E-05	0.9980	1.4
5	8	2002	19	0.9977	3.87E-05	0.9976	0.9
30	7	2002	17	0.9976	2.17E-04	0.9974	4.7
5	8	2002	21	0.9972	1.14E-04	0.9971	2.2
31	7	2002	20	0.9970	5.03E-05	0.9969	0.9
31	7	2002	19	0.9957	6.39E-05	0.9956	0.8
15	8	2002	19	0.9955	6.03E-04	0.9949	6.8
15	8	2002	20	0.9950	9.24E-04	0.9940	9.2
14	8	2002	18	0.9946	1.30E-04	0.9945	1.3
14	8	2002	21	0.9946	4.02E-04	0.9942	3.9
15	8	2002	18	0.9920	3.41E-03	0.9886	19.4
5	8	2002	18	0.9880	3.98E-04	0.9876	1.8
15	8	2002	17	0.9852	5.45E-04	0.9847	2
16	8	2002	20	0.9847	4.80E-04	0.9842	1.7
16	8	2002	19	0.9842	3.18E-04	0.9839	1.1
15	8	2002	21	0.9840	1.83E-03	0.9822	6
1	8	2002	20	0.9827	1.74E-03	0.9809	5.3
13	8	2002	20	0.9826	3.81E-04	0.9822	1.2
14	8	2002	17	0.9822	5.54E-04	0.9817	1.7
2	8	2002	19	0.9804	2.95E-03	0.9775	7.8
1	8	2002	19	0.9779	1.31E-03	0.9766	3.2
2	8	2002	20	0.9774	2.39E-03	0.9750	5.6
30	7	2002	22	0.9770	3.33E-04	0.9767	0.8
5	8	2002	17	0.9759	5.25E-04	0.9754	1.2
16	8	2002	18	0.9733	5.30E-04	0.9728	1.1
31	7	2002	21	0.9715	4.11E-04	0.9711	0.8
1	8	2002	21	0.9710	5.60E-03	0.9654	9.9
29	7	2002	21	0.9706	8.52E-04	0.9697	1.6
13	8	2002	21	0.9701	6.48E-04	0.9694	1.2
16	8	2002	21	0.9699	7.61E-04	0.9692	1.4
29	7	2002	20	0.9699	8.71E-04	0.9690	1.6
30	7	2002	16	0.9697	1.10E-03	0.9686	2
16	8	2002	17	0.9684	5.68E-04	0.9679	1
13	8	2002	19	0.9680	8.08E-04	0.9672	1.4
2	8	2002	18	0.9660	2.31E-03	0.9637	3.7
31	7	2002	18	0.9600	7.12E-04	0.9593	1
19	8	2002	20	0.9591	4.79E-03	0.9543	6.3
1	8	2002	18	0.9573	8.89E-03	0.9485	10.8
26	6	2002	20	0.9572	5.31E-04	0.9567	0.7
14	8	2002	22	0.9557	1.74E-03	0.9540	2.2
26	6	2002	19	0.9547	6.41E-04	0.9541	0.8
3	7	2002	19	0.9510	1.65E-03	0.9494	1.9
15	8	2002	22	0.9461	2.59E-03	0.9435	2.7
2	8	2002	21	0.9429	9.93E-03	0.9330	9.3

[a] Because of independent rounding, the predicted probability in the seventh column plus the predicted incremental probability do not add up to equal the predicted probability in the fifth column.

are consistent with expectations. Except for *FL*, these coefficients are also statistically significant as evidenced by their p-values. As hypothesized, the coefficients corresponding to $PSFL^3$ and $NSFL^3$ are negative and positive, respectively. Both coefficients are statistically significant. Also as hypothesized, the coefficients on the variables *SI* and *SE* are positive and negative, respectively. However, of the two coefficients, only the coefficient on *SI* is statistically significant. The coefficients corresponding to DPC^{-2} and DPG^3 are statistically significant and the estimated marginal impacts

Table 7. System Conditions, the GIC Proxy, and the Predicted Probability of a Reactive Off-Cost Event

Vulnerability Percentile in the Absence of Space Weather	Probability of an Off-Cost Event in the Absence of Space Weather	Value of the GIC Proxy (in nT/min) That Would Increase the Probability of Reactive Off-Cost Event to 0.51	Value of the GIC Proxy (in nT/min) That Would Increase the Probability of a Reactive Off-Cost Event to 0.75	Value of the GIC Proxy (in nT/min) That Would Increase the Probability of a Reactive Off-Cost Event to 0.95
5th	0.0055	284	342	445
10th	0.0108	248	305	408
25th	0.0279	195	253	355
50 th	0.0643	148	205	308
75 th	0.1215	110	167	270
90 th	0.2110	74	131	234
95 th	0.3318	40	98	200

are consistent with expectations when the values of the exponents are considered. The estimated marginal impact of PGC^{-2} is also consistent with expectations, and the coefficient is highly statistically as evidenced by its *p*-value.

[54] With respect to the model's explanatory power, note that it is not possible to calculate a conventional R-squared that is meaningful because the dependent variable is binary while the predicted values are probabilities. A number of alternative scalar fit measures have been introduced. According to *Greene* [2002, E15–28], these measures "… share the flaw that none satisfactorily mimic the true measure of the proportion of variation explained given by R^2 in the linear regression context."

[55] McFadden's R-squared is one of the more commonly reported measures of scalar fit when the dependent variable is binary. Its value here is 0.211. This value indicates that the log likelihood function, the objective function whose maximization yields the estimated parameters, improves by about 21% compared to when the model is estimated with only a constant term as an explanatory variable. The percentage of correct predictions is a more meaningful measure of the scalar fit. Using 0.5 as the threshold for a prediction of a reactive off-cost event, the percentage of correct predictions when on-cost status is predicted equals 91%, while the percentage of correct predictions when off-cost status is predicted equals 70%. The latter percentage is approximately 90% when the predicted probability is greater than 0.80.

[56] The econometric results presented in Table 4 should not be taken as definitive proof that GICs contribute to challenged reliability. Statistical methods alone cannot render results that establish or reject causality between two variables that are contemporaneously correlated. For this reason, ad hoc approaches to address the issue of causality are methodologically unsound. Instead, the results of inferential statistical analyses indicate whether the data are consistent with the hypothesis under consideration.

[57] There are three logical explanations for the results presented in Table 4. First, consistent with *Molinski* [2002], *Kappenman* [2003], and PJM's implementation of its solar magnetic disturbance procedures, GICs contribute to adverse reactive power conditions as hypothesized. Second, there is reverse causation, i.e., adverse reactive power conditions cause the GICs. Third, GICs do not contribute to adverse reactive power conditions; instead an omitted variable that is highly correlated with GICs is the true cause. The second possibility does not appear likely given that solar activity and the resulting properly measured GIC proxy are truly exogenous variables. With respect to the third possibility, we have yet to learn of an excluded terrestrial variable that contributes to adverse reactive power conditions and is also highly correlated with GICs. We suspect that others would be equally challenged in this regard. In short, the results presented here would not be easily dismissed by anyone with knowledge of the effects of GICs on reactive power consumption and formal training in multivariate inferential statistics. Others are free to adopt their own criteria. For example, some may consider our results acceptable only if the relationship is visually apparent using a scatter diagram or graph. Yet many important relationships do not meet this "visually apparent" criterion, e.g., smoking and lung cancer, a relationship that was established in large part using inferential statistics [*Parascandola et al.*, 2006]. While a scatter diagram can illuminate a relationship between the variables *X* and *Y* when the *Y* is a function of only *X*, it can fail miserably when *Y* is a function of more than one variable.

[58] Table 5 presents a listing of 50 market periods in which the predicted probability of a reactive off-cost event was significantly elevated by space weather. This listing reports the predicted probability based on terrestrial considerations along with the predicted probability based on terrestrial plus space weather considerations. Depending on geomagnetic conditions, the difference in the two predicted probabilities can be significant. For example, based on terrestrial conditions only, the predicted probability of a reactive off-cost event in hour 14 of 29 October 2003 equals 0.122; when the impact of geomagnetic conditions is factored in, the predicted probability is 0.722. It may be worth noting that PJM's solar magnetic disturbance procedures were implemented during this market period. For these 50 h, the median predicted probability of an off-cost event (0.2849) is more than double the predicted probability when only terrestrial determinants of the events are considered (0.1259). To put the results in perspective,

Table 6 presents a listing of 50 market periods in which the predicted probability of a reactive off-cost event was not significantly elevated by space weather.

[59] Table 7 presents the results of an analysis of the predicted probabilities. The predicted probabilities in the absence of the GIC proxy were first calculated and sorted. At the fifth percentile of the predicted probabilities, the terrestrial-based probability of a reactive off-cost event is 0.0055, while at the 95th percentile the probability equals 0.3318. Table 7 then reports the value of the GIC proxy that would be needed to increase the predicted probability to 0.51, 0.75, and 0.95. At the 5th percentile of the terrestrial-based probabilities (column two), the GIC proxy would need to equal 284, 342, and 445 nT/min. for the predicted probability of a reactive off-cost event to rise to 0.51, 0.75, and 0.95, respectively. In contrast, at the 95th percentile of the terrestrial-based probabilities the GIC proxy would only need to equal 40, 98, and 200 nT/min. for the predicted probability of an off-cost event to rise to 0.51, 0.75, and 0.95, respectively.

7. Conclusion

[60] This paper has addressed whether geomagnetic activity was a challenge to power system reliability during solar cycle 23 for the PJM regional transmission organization in North America. We examined the relationship between a GIC proxy and a metric of challenged reliability using the logit statistical method with statistical controls for expected system conditions. The results indicate that while there is no evidence of a space weather induced blackout in PJM during solar cycle 23, PJM's operations were nevertheless challenged by geomagnetic activity. The findings are consistent with previous literature. The results are also consistent with PJM's implementation of its solar magnetic disturbance procedures during the Bastille Day storm in July 2000 as well as during the Halloween Storms in October 2003.

[61] The analysis contained in this paper also indicates that the GIC/reactive power vulnerability of the power system is contingent on system conditions at the time of the geomagnetic storm. A storm would truly need to be a super storm to induce a reactive off-cost event when the terrestrial-based vulnerability of the system is low. In contrast, our results indicated that a modest geomagnetic storm could easily give rise to a reliability challenge when the terrestrial-based vulnerability of the system is high. This finding may have implications for mitigating the overall electric power reliability challenge. While space weather forecasting is in its infancy, the results of this analysis suggest that it is possible to forecast the terrestrial-based vulnerability of the power system. Inspection of Table 6 suggests that such forecasts may have the potential to enhance reliability even when the role of space weather is minor. These forecasts may also have the potential to better inform system operators about the space weather vulnerability of their systems, which would position them to make better use of space weather forecasts.

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