First GIC Estimates for the Mexican Power Grid

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Abstract This contribution addresses the first assessment of the impact of geomagnetically induced currents (GIC) on the 400-kV power grid of Mexico. As an initial approach, we modeled GIC using a uniform conductivity for the entire Mexican territory and spatially uniform geomagnetic disturbance. Power grid data were provided by the electric operator of Mexico; the geophysical data were inferred from the main features of Mexican geology. We calculate the power grid response during four geomagnetic storms from Solar Cycles 23 and 24 (i.e., 15 July 2000, 20 October 2003, 17 March 2015, and 7 September 2017), as well as during an extreme scenario (a Carrington-like event). The results show that the Mexican power grid can be affected by three-phase GIC ranging from 20 to 75 A during geomagnetic disturbances. According to the model, sites located in coastal areas or close to the edges of the network can experience large GIC during time intervals between 3 and 10 hr, depending on the intensity of the geomagnetic disturbance. It is an interesting result that these sites are of the major economic and strategic significance for the country. In the case of a Carrington-like event, the power grid could be affected by GIC ranging between 25 and 150 A under a uniform 1 V/km EW geoelectric field. Such an event might produce significant distortions in the grid hardware (i.e., transformers and static VAR compensators), potentially leading to widespread damage.

1. Introduction

Geomagnetically induced currents (GIC) are produced from the effects of magnetic storms at the Earth’s surface and flow in electrically earthed technological systems (Pirjola, 1985). Traditionally, such phenomena were considered limited to the auroral latitudes. Recent studies suggest, however, that space weather effects are important even at low latitudes as a result of the growing interconnection between isolated national power grids (Barbosa et al., 2015). GIC pose a threat to the integrity of power grids at low to middle latitudes (Carter et al., 2016; Gaunt, 2014). Currently, there is an increasing concern about the effects caused by space weather to national economies (Oughton et al., 2019; Eastwood et al., 2018; Lilensten & Bornarel, 2006).

GIC are a regional phenomenon that can affect large geographic areas depending on several factors, such as the degree of interconnection between different electrical networks, geological properties of the ground, and the topology of the electric grids (Zheng et al., 2013; Molinski, 2002). Because of their low frequencies (10−1–10−4 Hz), GIC are considered as a quasi-DC current superposed on the AC in the power lines. The GIC flow on all AC phases through the earthing connections, offsetting the transformers’ flux balance. This produces a half-cycle saturation, reactive power consumption and overheating, among other harmful effects, (Kappenman, 2013). In 2014, the General Civil Protection Act in Mexico incorporated the effects of space weather events into the list of natural hazards (Congreso de México, 2014). As a consequence, there was a mandate to federal agencies to design protocols to improve the country’s resilience toward these natural hazards. This motivated the creation of the Mexican Space Weather Service (www.sciesmex.unam.mx) in 2014 and the National Space Weather Laboratory (www.lance.unam.mx) in 2016 (Gonzalez-Esparza et al., 2016).

Since 2018, the Mexican Space Weather Service and the Federal Commission of Electricity (CFE) have established a collaboration to assess GIC impacts on the 400-kV power grid. Currently, it is the only GIC monitoring project active in Latin America (Denardini et al., 2016). In the following section, we describe the Mexican power grid and model details. Section 3 describes the events studied and the input data used to cal-

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2. Methodology

2.1. Mexican Power Grid Characteristics

According to the report of the Programa de Desarrollo del Sector Energético Nacional, from Mexico's energy secretary, the Mexican power grid is composed of two main networks, which employ ∼54,600 km of transmission lines at 400 and 230 kV, respectively. Both networks interconnect approximately 300 substations with a total transmission capacity of 76.7 GW. The 400-kV network studied is composed of 115 substations, which in most cases have multiple connections between them. All the 400-kV substations are connected by three-phase lines. The whole power grid has 13 interconnections with the US and Guatemala, covering almost 20° in latitude and longitude with long branches in the N-S and E-W directions, and it is managed by the CFE, a government institution. In this sense, the geographical characteristics of the Mexican territory can play an important role. The existence of coastal power lines with thousands of kilometers in length might favor the development of large GIC because of the ground conductivity contrast between the oceans and the continental landmass (Molinski, 2002). Figure 1 shows the topology of the 400-kV network throughout the Mexican territory.

2.2. The Power Grid Model

Because of the lack of detailed information about the 230-kV network, we focused on the 400-kV grid. Its high operation voltage and lower conductor resistances can make this network more vulnerable to GIC effects (Radasky & Kappenman, 2010). According to Zheng et al. (2014), GIC intensity is closely related to the system characteristics (e.g., mean conductor lengths and resistances). Therefore, neglecting the 230-kV network can produce a slight overestimate in the final results. We applied the Lehtinen-Pirjola nodal admittance method for modeling the 400-kV grid (Lehtinen & Pirjola, 1985). Figure 2 shows how the 400-kV grid...
In the nodal admittance method the grid is modeled as a network of grounded nodes connected by ideal current sources $J_n$ and admittances $y_{ij}$ in parallel. Each node is grounded by an earthing admittance $y_n$.

The admittances $y_{ij}$ and $y_j$ are defined as

$$y_{ij} = 1/R_{ij},$$

$$y_j = 1/r_j,$$

where $R_{ij}$ and $r_j$ are the conductor and earthing resistances, respectively. The current sources $J_j$ represent the GIC generated at each segment.

Network data such as node locations and the average resistance values of lines and transformers were provided by Mexico’s power operator as part of its collaboration with the National Autonomous University of Mexico (UNAM). We considered a uniform ground conductivity $\sigma = 0.007$ S/m. This value is the average conductivity of all the common physiographic provinces that compose the Mexican and southern U.S. territories (Fernberg, 2012).

The 400-kV lines are composed of three bundled conductors per phase. The conductors’ resistance was set to 0.026 $\Omega$/km, and all phases and circuits were reduced to one line. This value was provided by the electrical company as a mean value for all the conductors that compose their HV lines. The grounding resistances $r_g$ were set to 0.7 $\Omega$, according to the IEEE and NRF-011-CFE-2004 company standards (IEEE, 2015). The grounding resistance includes transformers’ winding resistances, which, in this case, was considered the same for all the substations excepting the connections with other power grids. At these connections, the corresponding $r_g$ values were decreased by 30% to take into account the existence of the outer network. The choice of such a value is empirical and is equivalent to replacing the outer power grid by an equivalent resistance (Boteler et al., 2013). For the cases where there are multiple power lines connecting a pair of substations across different paths, we set up an equivalent current-source admittance pair to account for the EM induction in all the single power lines. Connections to the U.S. power networks were neglected because they are made through asynchronous links at a lower voltage, as well as on the Guatemalan side, where the 400-kV network ends at the Los Brillantes substation, near the Mexican border. In this case, we followed a similar approach as in Caraballo et al. (2013) and Horton et al. (2012).

The geomagnetic disturbance was numerically calculated using magnetic data from the Magnetic Observatory of Teoloyucan located close to Mexico City. Because of the lack of other geomagnetic stations in the area, we assumed a uniform spatial distribution for $dB/dt$ throughout the Mexican territory. The geoelectric field $\mathbf{E}$ was calculated by means of the convolution integral:

$$E(t)_{x,y} = -\frac{1}{\sqrt{\mu_0 \sigma}} \int_0^\infty \frac{g(t-u)}{\sqrt{u}} du,$$

where $g = dB/dt$ are the derivatives of the horizontal components of the $\mathbf{B}$ field at the Earth’s surface (with $x$ and $y$ denoting the northward and eastward components, respectively). Note that in equation (2), E-field values at a given time $t$ depend on previous values of $g$ as the integration domain is the $[t, \infty)$ interval. Because of the discrete nature of the magnetic time series, the integral in equation (2) was calculated by following Simpson’s 3/8 rule (Abramowitz & Stegun, 1964). Once $\mathbf{E}$ is calculated, the geovoltage between substations $i$ and $j$ is obtained by integrating along the power lines as in equation (3):

$$V_{ij} = \int_i^j \mathbf{E} \cdot d\mathbf{r},$$

with

$$\mathbf{E} = -\nabla \Phi + \partial \mathbf{A}/\partial t.$$

In equation (4), the geoelectric field $\mathbf{E}$ is the combination of a scalar potential $\Phi$, caused by the charges present in the integration volume and a potential vector $\mathbf{A}$ produced by the current sources. Hence, $\mathbf{E}$ is not conservative. The GIC at each grounding point can be obtained by solving the matrix equation (Boteler, 1997).
Table 1

| Date           | SC  | min Dst(nT) | max Kp |
|----------------|-----|-------------|-------|
| 2000-07-15/16  | 23  | −180        | 9o    |
| 2003-10-29/30  | 23  | −350        | 9o    |
| 2015-03-17/18  | 24  | −222        | 8−    |
| 2017-09-07/08  | 24  | −124        | 8+    |

\[
I = (\mathbb{1} + YZ)^{-1}J,
\]

where \(I\) is a \(N \times 1\) matrix with elements that are the earthing currents at the nodes at each instant, \(\mathbb{1}\) is the identity matrix, \(Z\) represents the earthing impedance matrix, and \(Y\) represents the admittance matrix with elements defined as

\[
Y_{ij} = \begin{cases} 
-\frac{1}{R_{ij}} & i \neq j \\
\sum_{k=1, k \neq i}^{n} \frac{1}{R_{ik}} & i = j
\end{cases}
\]

where the indexes \((i, j, k)\) denote network nodes. In the case of distant substations (i.e., nodes), \(Z\) is a diagonal matrix with elements that are the earthing resistances \(r_g\). In the case of the Mexican grid, the minimum separation between substations is greater than 10 km; hence, this approximation is applicable.

The last term, \(J\), is a column matrix with elements that are defined as

\[
J_i = \sum_{j=1, j \neq i}^{n} \frac{V_j}{R_{ij}} (i, j = 1...n).
\]

In addition, its elements represent perfect earthing currents (i.e., \(Z=0\)) between each pair of nodes. The electrical parameters of the grid are the input for the definitions of \(Y, Z\) and \(J\). Likewise, the ground conductivity \(\sigma\) is required in the determination of \(E\). Therefore, GIC modeling requires the combination of both geophysical and engineering inputs. Uncertainties in those inputs will affect the final results depending on the grid characteristics and on the ground properties (Caraballo, 2016; Beggan, 2015).

3. Study of Four Geomagnetic Storms

Four geomagnetic storms were chosen to assess the grid response to a strong geomagnetic disturbance. Two events from the Solar Cycle 23 were considered: the Bastille Day storm on 15 July 2000 and the Halloween storm on 29 October 2003. Two magnetic storms from Cycle 24: the St Patrick’s day storm on 17 March 2015 and 7 September 217, respectively. These events were chosen considering their relevance, severity, and effect on the Earth’s environment. We used the minimum Dst and maximum Kp as proxies of their severity. As seen in Table 1, the magnetic storms were larger in Solar Cycle 23. Bastille Day storm was triggered by a X5.7 solar flare on 14 July 2000, which occurred near the peak of the solar maximum. The flare subsequently caused an S3 radiation storm. It was the biggest solar radiation event since 1989 (Roylance, 2000). The proton event associated with the flare was four times more intense than any previously recorded since the launches of SOHO in 1995 and ACE in 1997 (Zhang et al., 2003). The flare was followed by a massive full halo CME, which produced an intense geomagnetic storm on 15 July. The geomagnetic storm peaked at the extreme level in the late hours of 15 July. The Bastille Day event’s effects were observed at the distance by both Voyager 1 and 2 spacecraft (Webber et al., 2002). The second geomagnetic storm of this study is related to the Halloween storms triggered by a series of intense flares (X17.2) and several CMEs peaking around 29 and 30 October 2003. This event generated the largest solar flare ever recorded by the GOES system. Satellite-based systems and communications were affected, aircraft were advised to avoid high altitudes near the polar regions, and long power outages occurred in Sweden and South Africa as a result of the solar activity (Gaunt & Coetzee, 2007; Pulkkinen et al., 2005). The third event chosen was the St. Patrick’s Day magnetic storm on 17 March 2015. A fast CME hit Earth’s magnetic field on 17 March at approximately 04:30 UT. At first,
Figure 3. Maximum GIC currents calculated at each substation of the Mexican 400-kV grid. The color and size of the circles are proportional to GIC intensity according to the color scale. Each panel represents the Halloween Storm on October 2003 (a), the Bastille Day storm on July 2000 (b), the September 2017 storm (c), and the March 2015 storm (d). The SYM-H index (blue) and calculated $E_y$ (red) are plotted in the insets below each graph. Magenta marks inside denote the time interval when the GIC exceeded 30 A anywhere. The most affected substations are Riviera Maya (RMY), Laguna Verde (LAV), Tres Estrellas (TTE), Altamira (ALT), Rio Escondido (REC), Moctezuma (MCZ), Nacozari (NCZ), and Mazatlán (MZD).

The impact sparked a relatively mild G1 ($K_p = 5$) geomagnetic storm. Afterward, the storm intensified to a G4 ($K_p = 8$), ranking it as one of the strongest magnetic storms of the Solar Cycle 24. In this case, the $B_z$ component of the IMF stayed north but turned south by some hours to $-26$ nT (Zhang et al., 2017, and references therein). The September 2017 events included an X9.3 flare and a G4 magnetic storm (Redmon et al., 2018). In addition, Gonzalez-Esparza et al. (2018) reported the September 2017 space weather events detected by the Mexican ground-based instrumental network.
Space Weather

Figure 4. Temporal evolution of the GIC at each substation. GIC intensity is represented in grayscale, and each panel represents an event. Most affected substations are marked by their acronyms (see Figure 3). The vertical axis represents the substation index, and the horizontal one is the time in minutes since the beginning of the day of the storm commencement.

We considered a two-day window starting at 00:00 UT of the day of the storm commencement (excepting the Halloween Storm, because Teoloyucan magnetic observatory provided only 34 hr of geomagnetic coverage). Figure 3 shows the response of the Mexican grid during the four magnetic storms. The panels indicate the total GIC intensity into each substation’s grounding grid (i.e., the sum of GIC in all phases).

The results point out interesting aspects of the grid. Substations located close to the coast or at the edges of the network show higher GIC activity (e.g., Riviera Maya, Nacozari, Mazatlán, and Laguna Verde nuclear power plant). Note that several major power plants are located at these sites. On the other hand, inland substations show moderate GIC intensities that do not exceed 25 A. This is the case of the substations within the power rings surrounding Mexico City, Monterrey, and Guadalajara, respectively. Insets in the Figure 3 panels show the SYM-H index and calculated $E_y$ component, respectively, as proxies of the severity of each event. Magenta lines mark the time intervals where the GIC exceeded 30 A on the grid, and they provide an estimate of the duration of the GIC phenomenon for each event. In the case of the Bastille and Halloween storms, this time interval ranges between 7 and 10 hr, respectively. On the other hand, during the September 2017 magnetic storm, intense GIC lasted only for 49 min. In all cases, the GIC reached their maxima during the storm’s main phase.
Figure 5. Normalized histograms of the orientations of the geoelectric field during the events studied. The E-field shows a strong tendency to remain pointing eastward (i.e., 0°). During the Halloween and September 2017 storms, the E-field was confined to a narrow angular sector around the east direction. In the case of the Bastille and St. Patrick’s storms the E-field showed a broad variation of ±50° around the east direction. The N value inside each box is the number of data points. The horizontal axis is as follows: east = 0°, north = 90°, south = −90°, and west = ±180°.

Figure 4 shows the temporal evolution of the GIC at each substation for the four events. The stack plots consist of 115 grayscale ribbons each representing a substation. All substations were indexed; the vertical axis represents the substation index, while the horizontal one corresponds to the time in minutes from the beginning of the storm day. Acronyms of the most affected substations were annotated on the right side of each plot (see caption in Figure 3). The stacked plots provide a complete glimpse of GIC activity in the network. As in Figure 3, we can see that about 80% of the substations registered GIC values over 20 A in the four events. Despite its low-latitude location, the Mexican grid is broad and has long power lines in both N-S and E-W directions. Note that the values plotted in Figures 3 and 4 show the total GIC currents that are distributed through all the conductors of the power lines connecting to each substation. With these GIC values, we would expect a strong contribution to harmonics generation and reactive power demand, capable of triggering the protection systems (Kappenman, 2007).

Regarding the geoelectric field behavior, Figure 5 shows the orientation distributions of the E-field for the four events in the form of normalized histograms. The E-field data were grouped into 60 angular bins, each one covering an angle of 6° in direction. In all cases, the E-field remained predominantly in the E-W direction.
Figure 6. Hypothetical events that could lead to an E-field of 1 V/km in E-W (up) or N-S directions (down). In both cases, the largest GIC intensities occurred close to the ends of the branches with an orientation parallel to each direction.

during long intervals, reaching its highest frequency values. Except for the Halloween and September 2017 storm events, where the E-field remained almost confined to a narrow interval of directions, the rest of the events show a broad dispersion of directions around the East direction. In some cases, the angular spread reaches the NE-NNE directions (100°), as in the case of the Bastille and St. Patrick’s Day storms.

3.1. A Carrington-Like Event Scenario
González-Esparza and Cuevas-Cardona (2018) reported that the red aurora, associated with the Carrington geomagnetic storm in 1859, was observed and reported from at least seven different sites in Mexico. In order to assess the grid response to such extreme events, we calculated the GIC in the power grid produced by a uniform 1 V/km E-field in the E-W and N-S directions, respectively. This is a typical value of high-latitude geoelectric field that has been reported in several publications (Myllys et al., 2014; Pulkkinen et al., 2008). Geoelectric field intensities are strongly dependent on the geomagnetic latitude, and reported values at low latitudes never exceeded 500 mV/km during the Halloween storm, the most intense event registered in the
last decades (Zheng et al., 2013; Caraballo et al., 2013; Bernhardi et al., 2008). Thus, such field values at lower latitudes are unlikely unless we experience a great geomagnetic disturbance. The results in Figure 6 for these scenarios show that, regardless the geoelectric field orientation, substations located at the edges of the grid and in coastal areas show large GIC levels ranging between 25 and 150 A. Figure 6 shows that the most affected substations in each case are located at the ends of branches almost parallel with the E-field.

4. Discussion

Note that this model has limitations because it uses strong assumptions. First, regarding the spatial uniformity in the time variation of the geomagnetic field, Mexico has one magnetic observatory located in Teoloyucan, near Mexico City. There is a lack of geomagnetic coverage in the southern part of the country. Such an assumption can lead to some discrepancies with respect to the actual GIC levels. As we cannot provide a dense network of geomagnetic stations into the territory, it would be necessary to interpolate the geomagnetic disturbance at each point by means of some mathematical algorithm, such as the complex image method or the spherical elementary currents system (Boteler & Pirjola, 1998; Amm, 1997), in order to provide dB/dt at each point within the country. In this case, to perform the interpolation of the geomagnetic disturbances, we can take into consideration some magnetic observatories at the southern border of the United States and the Teoloyucan magnetic observatory. Second, there are no magnetotelluric data available for Mexico in order to directly determine its ground conductivity structure. The use of regionally averaged conductivity models adds uncertainty to the orientation of the geoelectric field. This forced us to use a uniform ground conductivity based on the geological data available as stated in section 2.2. Third, the effect of the 230-kV grid was neglected because of a lack of information about its electrical parameters. This can produce a slight overestimation in the final GIC results. Lower voltage networks can be modeled as equivalent resistances at the interconnection points (Boteler, 2013). However, studies made at other low-latitude countries where lower voltage networks were neglected showed that their effect can be slight (Barbosa et al., 2015; Bernhardi et al., 2008). The results indicate that substations located near the edges of the grid can be affected during geomagnetic storms, while the inland ones show more resilience. For now, this can be ascribed entirely to the grid topology. Substations located close to coastal areas may suffer additional effects due to charge accumulation induced by the contrast of conductivity between the ocean and landmass (Molinski, 2002). At these sites, the GIC have few paths to flow into, being restricted to move inwards or outwards of the ground exclusively. A further study with a two-dimensional ground conductivity profile can show such influence but is still in progress. In the case of inland substations, the lower GIC values can be ascribed to the great number of close substations where the GIC have the chance to spread through multiple grounding points. The proximity between substations leads to short branches that prevent the development of large potential differences.

From Figures 3 and 4, we can conclude that the Halloween storm led to the strongest GIC levels in the grid. Moreover, the event duration and calculated geoelectric field intensities were the largest, lasting 10 hr and reaching 400 mV/km in the E-W direction, respectively.

By analyzing the Carrington-like events in Figure 6, we can conclude that the power grid can be severely affected whether the E-field direction is E-W or N-S. This can be ascribed to the existence of two main axes in the grid, which run almost parallel to these directions.

To ensure the reliability of the model, we performed a benchmark analysis considering the most extreme set of input parameters, which led to admissible results (Figure 7). We used an empiric criterion based on the maximum GIC, which is likely to be observed during a magnetic disturbance like the Halloween storm in 2003. We set the maximum admissible GIC to 150 A. According to the literature, such a value is unlikely to be observed at low-latitude countries since reported GIC at these latitudes rarely exceed 20 A for the same event (Torta et al., 2017; Barbosa et al., 2015; Wik et al., 2009; Bernhardi et al., 2008). The parameters considered were conductor and grounding resistances as well as ground conductivity. The uncertainty was tested for ground conductivity values within the interval (0.001 S/m ≤ σ ≤ 0.05 S/m), grounding resistances in the interval (0.02 Ω ≤ rg ≤ 1.2 Ω), and conductor resistances in the range between 0.0011 and 0.0527 Ω/m. Following our criterion, parameter combinations that led to GIC intensities above 150 A were discarded. Finally, we obtained a small set of combinations of the input parameters, which led to results similar to the
Figure 7. Benchmark of GIC levels expected, based on the most extreme values of the input parameters admissible for the model. The legend shows the most extreme parameter combinations that led to GIC values compatible with the observations made abroad. The bold blue curve corresponds to the maximum GIC level estimated in the Mexican 400-kV grid for the Halloween event.

observed ones in other countries (Carter et al., 2016). The extreme input values came from the available data in the standards for the power grid and from the geophysical data available for the Mexican territory. As seen in Figure 7, the results are more sensitive with respect to the ground conductivity \( \sigma \) and conductor resistances. The benchmark study, however, revealed that the actual GIC levels are likely to lie between the values plotted in Figure 7, even in the case of a 30% to 40% variation in the input parameters (Pulkkinen et al., 2006).

5. Conclusions and Final Remarks

A simple model of the 400-kV power grid has been studied in order to assess the GIC influence over the entire grid. Despite some overestimation caused by the neglecting of the lower voltage networks, the results show that the Mexican power grid can be affected by GIC during strong magnetic storms. We calculate GIC intensities at 115 substations of the power grid with data provided by the electric operator of Mexico and by using the limited geological data available in order to accomplish all the requirements of the model. Results show that substations located at the edges of the grid can be affected by GIC intensities ranging between 10 and 75 A (\( \sim 3 \) and 25 A per phase), regardless of the main orientation of the geoelectric fields. As Figures 3 and 4 show, most affected areas are of great economic and strategic value, which enhances the importance of studying space weather effects at such locations. The extreme scenarios analyzed, as in the case of a magnetic disturbance capable of producing a geoelectric field of 1 V/km (Figure 6), lead us to conclude that the Mexican power grid can be affected significantly in the case of a Carrington-like event. Furthermore, the results obtained in this case justify the necessity of an assessment of the grid response in case of an extreme geomagnetic event. The results obtained at this stage are being used to plan the installation of GIC sensors at the most critical sites. On the other hand, it is necessary to provide additional magnetic stations in the
south of the territory in order to enhance the reliability of the interpolation process. This initial estimate is part of an exploratory analysis for identifying potential sites for placing GIC sensors. Further validation will be performed once we can process measured GIC data.

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