# GIC

## User Requirements Document

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Issue 1

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# DOCUMENT STATUS SHEET

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# 1 INTRODUCTION

## 1.1 Purpose

The purpose of this project is to provide a software package that can be used for real time forecasting of geomagnetically induced currents (GIC) in the Swedish power grid. The software shall be used by power grid operators and tested for a one-year period. During this period, the accuracy and reliability of the software shall be determined, and the usefulness of the software shall be formulated through a cost-benefit analysis. Another aspect is the need to educate the public and decision makers of the potential hazards of GIC and how forecasts can help to mitigate the effects. Thus, the software shall also have a public part.

At a working meeting in April 2003 more specific requirements were obtained from Håkan Swahn, representing Elforsk. Among other things, useful ways of presenting GIC were discussed. As described in Section 2.1 the Swedish power grid is divided into substations and zones. Therefore, it would be useful to be able to get some average GIC disturbance for these regions.

## 1.2 Scope

The power grid operators need accurate forecasts of GIC from hours up to weeks in advance. Due to the nature of the physical system, one-hour forecasts should be possible using solar wind data. To push the forecasts further solar data are needed which leads to a much more complex problem. Therefore, this project shall focus on developing software for one-hour forecasts of GIC.

If a software system can be developed that accurately (see Section 2.5) forecasts the GIC values in Amperes with one-minute resolution, then it would suffice. However, there might be a number of problems that does not make this possible. Therefore, alternative ways of representing the GIC shall be explored that are of practical use.

As specified in the proposal the software should be capable of producing forecasts at all points in the Swedish power system. That requirement assumed that a database with the power grid description could be produced in a suitable format using existing software. However, this is not the case, which means that a greater effort is needed to create the power grid database. Therefore, only a subset of the Swedish power grid will be considered covering the south of Sweden.

## 1.3 Definitions, acronyms and abbreviations

| | |
|---|---|
| ACE | Advanced Composition Explorer |
| FMI | Finnish Meteorological Institute |
| GIC | Geomagnetically Induced Current |
| IMF | Interplanetary Magnetic Field |
| IRF | Swedish Institute of Space Physics (Institutet för rymdfysik) |
| NaN | Not a Number |
| NSSDC | National Space Science Data Center |
| OKG | Oskarhamns kraftverksgrupp |
| UL1 | User Level 1 |

| | |
|---|---|
| UL2 | User Level 2 |
| WDC | World Data Center |

### 1.4 References

1. Elforsk AB, `www.elforsk.se` .
2. ESA software engineering standards, ESA PSS-05-0 Issue 2, February 1991.
3. Guide to the user requirements definition phase, ESA PSS-05-02 Issue 1, October 1991.
4. NSSDC OMNIWeb, `www.nssdc.gsfc.nasa.gov/omniweb/`.
5. OKG AB, `www.okg.se` .

### 1.5 Overview

The structure of this document follows the document template as described in the ESA software engineering standards [1] and user requirements guide [3].

## 2 GENERAL DESCRIPTION

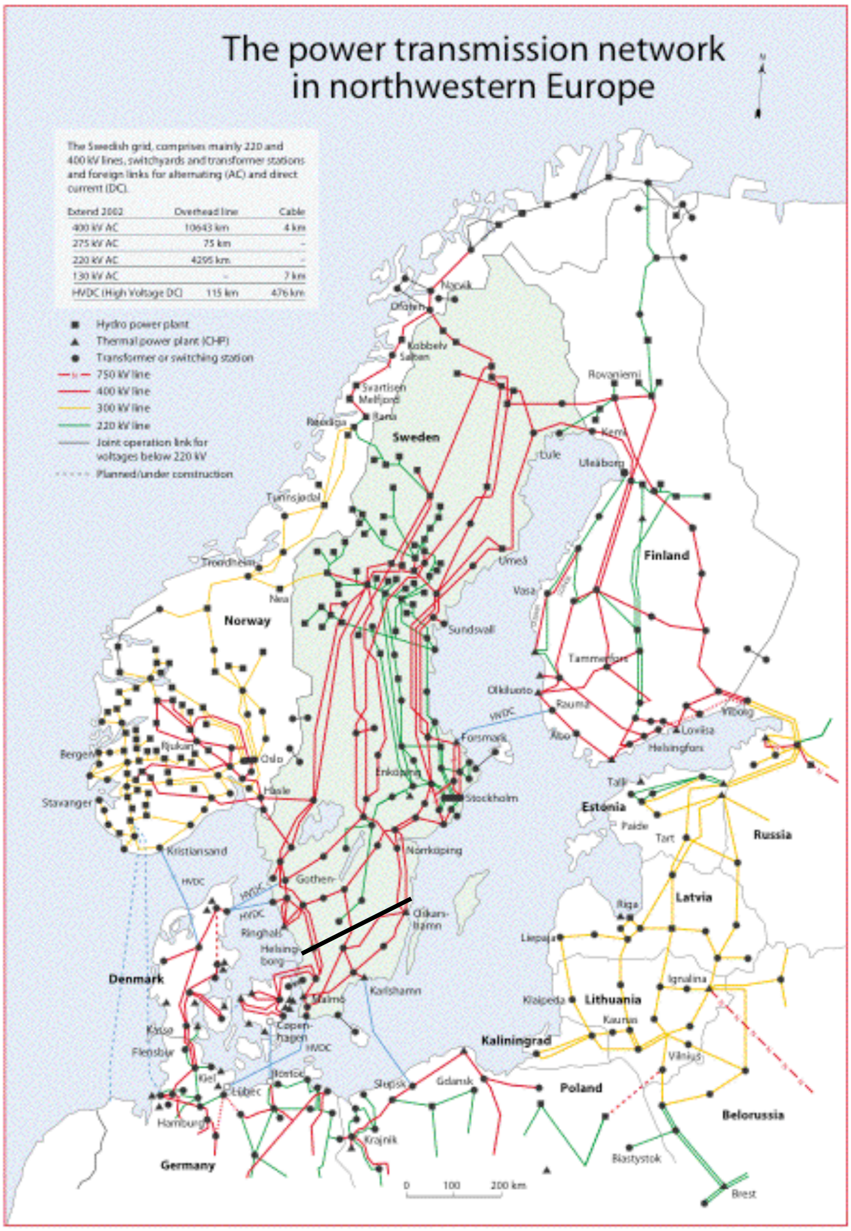
### 2.1 Product perspective

As stated in the introduction this software shall provide forecasts of GIC in Sweden. To support this, a model shall be developed that can predict GIC, where the model relies on solar wind data. When the software system is connected to the Internet real-time solar wind data can be used to provide forecasts. The system shall also contain a database with solar wind data so that predictions can be made on historic data. Thus, the system can run on-line to provide forecasts, or off-line to provide historic predictions.

There shall also be a graphical user interface to the system. On a map, similar to that of Fig. 1, the GIC shall be displayed in way so that locations with large GIC values are clearly visible. By clicking on specific locations on the map, the actual values will be displayed. It shall also be possible to display plots of time series of GIC over a period selected by the user.

The Swedish 130, 220, and 400 kV network consists of about 1300 transformers grouped into about 800 substations. The grid is also geographically divided into five zones from the north to the south. It is interesting to know the GIC in each transformer. Our approach is to develop a model that predicts the geoelectric field for any location in Sweden from solar wind data. Having a model of the power grid the GIC can then be computed in any transformer from the geoelctric field. The development will proceed in two steps: 1) first only the 220 kV and 400 kV lines will be included enabling the software system to be tested; 2) after successful testing the 130 kV lines will also be included.

In this project the model shall be developed to cover the south part of Sweden extending over zone 5 and approximately half of zone 4 just north of OKG (thick line in Fig. 1). Only the 220 kV and 400 kV lines shall be included.



The Swedish grid, comprises mainly 220 and 400 kV lines, switchyards and transformer stations and foreign links for alternating (AC) and direct current (DC).

| Extend 2002 | Overhead line | Cable |
|---|---|---|
| 400 kV AC | 10643 km | 4 km |
| 275 kV AC | 75 km | - |
| 220 kV AC | 4295 km | - |
| 130 kV AC | - | 7 km |
| HVDC (High Voltage DC) | 115 km | 476 km |

**Fig. 1.** The power transmission network in northwestern Europe. The line just north of Oskarshamn marks the modelled area.

## 2.2 Glossary

**Forecast**

When a model is run on real-time data the output is a forecast.

**GIC**

Geomagnetically induced current. It is either a positive or negative value in units of Amperes (A). The value in the line is three times the phase current.

**GIC index**

A parameterization of GIC.

**Prediction**

When a model is run on historic data the output is a prediction.

**Single line diagram**

The three phased power lines are summarized into a single line in the single line diagram.

**Substation**

A substation is a node that usually includes one or more transformers.

## 2.3 User characteristics

As stated in the introduction both power grid operators and the public shall have access to the system, thus we have identified two types of users. In addition, there is also the system manager. There shall be different levels of access to the system for the two types of users as will be described below.

### 2.3.1 System manager

The system manager shall have full access to the data, source codes, and documentation. During the development of the project the system manager shall be a person at IRF, but after successful completion this role can be shifted to Elforsk or ESTEC. This shall only be a hand-full of people that are involved in the development and the maintenance of the system. However, the power grid database is not allowed to be shifted anywhere without the approval of Elforsk.

The system manager should have a good knowledge of computers, web techniques, and Internet. He should have good knowledge in HTML, Java, and Matlab programming. He is also responsible for the extension of the database. However, all new data that are added must first be agreed by the project team.

All persons working on the project shall sign a confidentiality agreement concerning the power grid database.

### 2.3.2 User level 1: power grid operator

In the group of power grid operators, there are people who should make decisions out of the information given by the GIC forecast service. The interface shall give a clear view of the current GIC levels in the power grid. The interface shall contain a map of Sweden with the power lines and nodes similar to that of Fig. 1. The interface shall be interactive so that more information about GIC levels can be obtained for specific locations. The interface shall only be accessible to registered users.

### 2.3.3 User level 2: public

In the public group, there are people that may have an interest in GIC. In this group, we e.g. find scientists, decision makers, educators, and other pilot project SDAs. The material accessible to this group has its emphasise on outreach and education. The interface shall be a simplified version of that of the UL1 interface. Data or models that are available for UL1 that contain sensitive information shall not be accessible to UL2. The UL2 interface shall be accessible to any user.

## 2.4 General capabilities

### 2.4.1 Definition of prediction and forecast

In this document the term *prediction* is used when a model is applied to produce an output for any historic time. E.g., we can use the model to make a prediction of the March 13, 1989, event. In contrast, a *forecast* is made when the model is run on real time data so that a future value is obtained.

### 2.4.2 Geomagnetically induced current – GIC

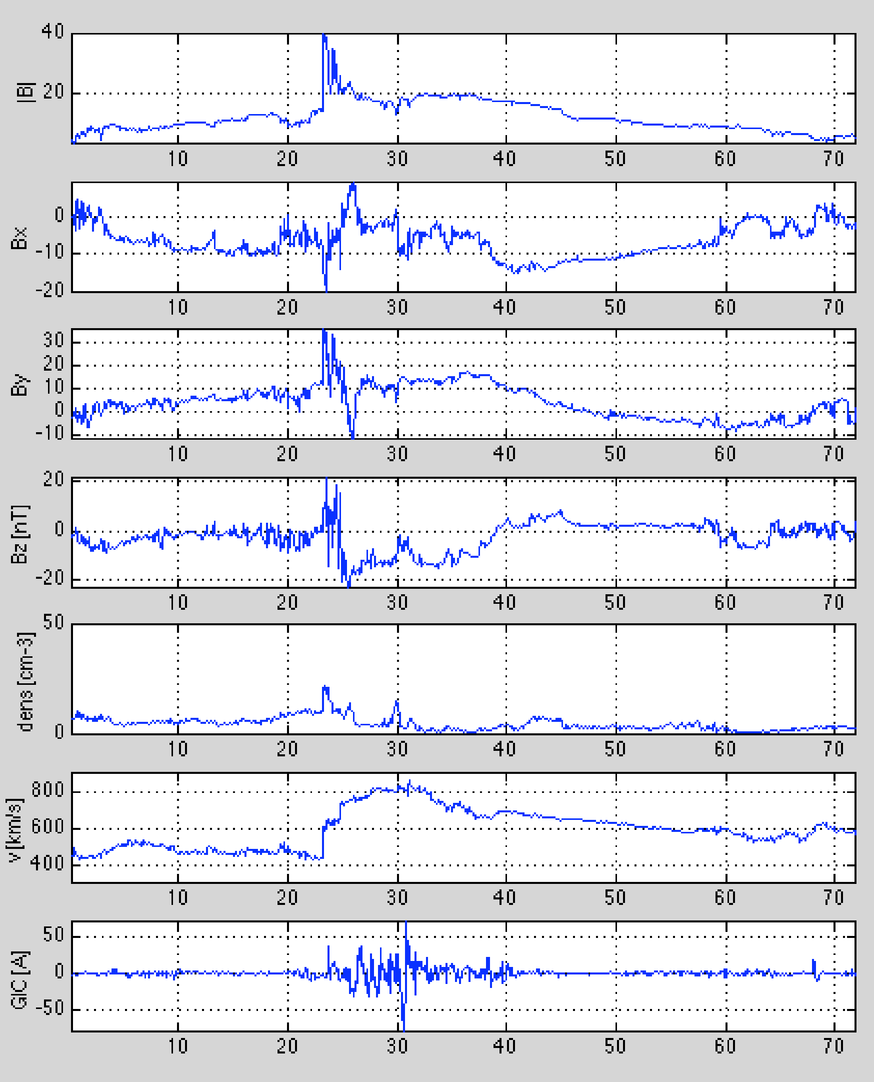


**Fig. 2.** The figure shows an example of a solar wind disturbance that drives a GIC in south Sweden. The top six panels show the solar wind: total magnetic field, x-component of the magnetic field, y-component of the magnetic field, z-component of the magnetic field, particle density, and velocity. The bottom panel shows the measured GIC. The x-axis is the time in hours from 24 September 1998.

### 2.4.3 GIC index

From a user perspective it is not necessary to know the exact evolution of the GIC. Instead, it might be more appropriate to have a parameterization of the GIC. A GIC has an onset time, a duration time, and an amplitude as illustrated Fig. 3. We call the parameterized GIC a GIC index. It shall be explored how the GIC index can be derived, and whether forecasting the index gives advantages over forecasting GIC values.

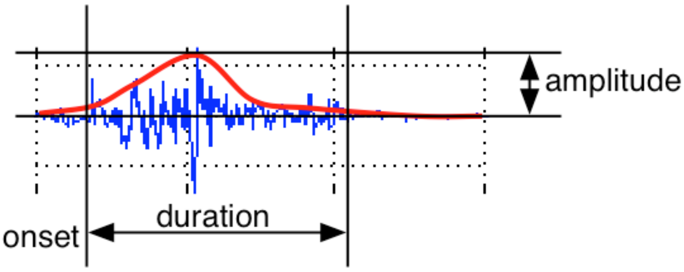


**Fig. 3.** The figure shows an illustration of how the GIC can be parameterized into a GIC index.

One major concern for the power companies is the thermal heating of the transformer due to the induced currents. Thus, both the duration and the amplitude of a GIC event are of importance. Therefore, it would be useful to predict the probability that the GIC exceeds a certain value for different time intervals. The suggested intervals are less than or equal to 5 minutes, 5–10 minutes, and more than 10 minutes.

### 2.4.4 Output from the software

The Swedish power grid consists of about 1300 transformers. Transformers that are geographically close and within the same fence are called substations. The transformers are organised into about 800 stations. Further, the stations are organized into five zones from the north to the south of Sweden.

The GIC occurs in transformers and power lines connecting the transformers and is a result of the geoelectric field. A GIC is characterized by rapid fluctuations with a certain amplitude and duration. With an accurate prediction of the geoelectric field detailed determination of the GIC should be possible.

Result files will be produced for benchmarking and further analysis.

### 2.4.5 Graphical interface for power grid operators

It will require repeated display experiments and feedback from the operators before a satisfactory design is achieved. During the first discussions, a sensitive web based map of the power transmission network, was suggested. For various thresholds, stations and zones having problems will be indicated by blinking lights. By clicking on the sections having problems further information will be given. The network grid shall be displayed as a single line diagram.

### 2.4.6 Graphical interface for the public

First an easy to understand introduction of how GIC can affect power systems and the causes will be given. It will contain animations and cases. Secondly, also predictions and forecasts will be illustrated. The interface will be web based and therefore easily accessible for the public.

### 2.4.7 Models

#### 2.4.7.1 Local differential magnetic field from solar wind

The solar wind drives the geomagnetic activity. The local magnetic field variations are determined from a number of different sources. However, we do not need to know the magnetic field itself but rather the time derivate dB/dt. A model shall be developed that can predict dB/dt from solar wind magnetic field and plasma data. The model inputs are solar wind magnetic field, density, velocity, and the geographic location of where dB/dt shall be predicted. The output is dB/dt. The three closest magnetic observatories shall be used to create the training, validation and test data. The observatories are located at Uppsala, Sweden; Brorfelde, Denmark; and Wingst, Germany.

The necessary temporal resolution of the predicted dB/dt has to be determined. The resolution is related to the desired accuracy of the electric field and GIC models described in Sections 2.4.7.2 and 2.4.7.3, respectively. The highest possible resolution is one minute using ACE real-time solar wind data. However, it might not be possible to develop a model that predicts dB/dt with one-minute resolution. Therefore, the optimal temporal resolution will be a trade-off between the two.

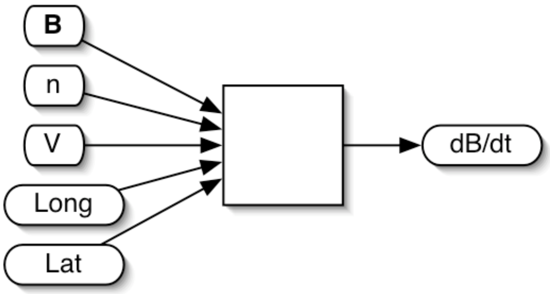


**Fig. 4.** The dB/dt prediction model has the inputs shown in the figure.

#### 2.4.7.2 Geoelectric field from the magnetic field

The horizontal geoelectric field at the Earth's surface is the driver of GIC in power networks and other technological systems. So, the first step in a GIC calculation is the determination of the geoelectric field in a sufficiently dense grid covering the network investigated. If the source currents in the ionosphere and magnetosphere and the Earth's conductivity distribution are known the geoelectric field can in principle be calculated in a straightforward manner. However, in practice the calculation is easiest to be performed by using available ground magnetic data and a relation between electric and magnetic fields at the Earth's surface. This relation is expressed by a frequency-dependent surface impedance, which characterises the ground conductivity at the particular site. Fourier and inverse-Fourier transforms permit the use of time-domain magnetic data and give the geoelectric field as a function of time.

#### 2.4.7.3 GIC from geoelectric field

After the geoelectric field is known, GIC in the network can be determined by using dc circuit theory. It requires that the geometrical and geographical configuration of the system and its resistances are known. For power systems, which are earthed at transformer neutrals, a convenient matrix formulation utilizing the "earthing-impedance matrix" and the "network-admittance matrix" is available. The calculation of GIC from the geoelectric field is straightforward and inaccuracies are probably mostly arising from the determination of the geoelectric field. Confidence factors will be given from comparisons of observed historical data and model-based calculations.

#### 2.4.7.4 Spatial statistics of predictions

It shall be possible to compute the spatial average and maximum values of the various predicted quantities covering different geographical regions. The choices of spatial scales are statistics on substation and zonal levels, respectively.

#### 2.4.7.5 Single transformer GIC forecast from solar wind

Accurate GIC data exist for one transformer in southern Sweden. An empirical model shall be developed that forecast the GIC in this transformer directly from the solar wind. Over the years the characteristics of the transformer have changed, due to changes in the grid by the grid owner, leading to changes in GIC levels not related to the space weather. This makes it difficult to use the model for real-time forecasts. However, it is still interesting to see how well such a model can perform for future developments.

### 2.4.8 Database

The models that shall be used for the GIC predictions are driven by solar wind data. The approach to predict GIC is to first predict the rate of change of the geomagnetic field (dB/dt) at the Earth’s surface at any given geographic location in southern Sweden (Sect. 2.1), and then compute the geoelectric field, and then finally GIC. The model predicting dB/dt is derived from observed solar wind data and dB/dt. To support the prediction models a database with observed space weather data is needed. The database shall contain the data described below.

#### 2.4.8.1 Solar wind data

There are two main sources for the solar wind data: the OMNI database and the ACE data.

The OMNI database contains hourly averages of the solar wind magnetic field, density, and velocity. It also contains various other solar-terrestrial data. The database covers the period from 1963 to 2002, where the last years have many missing values. The data are stored in annual files and can be obtained from ftp://nssdcftp.gsfc.nasa.gov/spacecraft_data/omni/.

The ACE spacecraft provides real time solar wind data. The time resolution is one minute. The latest data can be found at ftp://ftp.sec.noaa.gov/pub/lists/ace/.

#### 2.4.8.2 Geomagnetic data

The geomagnetic data comes from sites that are relevant to Sweden. The data have a resolution of one minute. Interpolating these data, the time derivatives of the horizontal components of the geomagnetic field are computed in a dense grid covering Sweden. Both the observed and the computed geomagnetic field shall be stored in the database.

#### 2.4.8.3 GIC data

Observed GIC data exist for a single transformer on the east coast of southern Sweden. The time resolution is one minute. GIC measurements are continuously made and data are recorded whenever the GIC goes above a threshold level. Currently the data are not available in real time.

#### 2.4.8.4 Power grid data

As GIC is a quasi-DC phenomenon, it is sufficient to have the following data of the power system: geographic locations of earthing points, routes of transmission lines, line resistances and transformer resistances including the earthing resistances. Although transmission lines are 3-phase, they will be described as single lines, so GIC in a line is understood as the sum of currents in the three phases. Special configurations like autotransformers or several transformers at a single site have to be indicated separately. Power systems to be included are at the highest voltage (400 kV), and possibly the 220 kV and 130 kV. During the pilot SDA, only the south part of Sweden is considered.

## 2.5 General constraints

As described in Section 1.2 this software shall be able to produce accurate one-hour forecasts of GIC. The goal is to achieve 95% accuracy of the zonal maximum absolute GIC and zonal average absolute GIC.

## 2.6 Assumptions and dependencies

The continuous update of the database assumes that the data discussed above are available in real time over the Internet. It is also assumed that the data format from those sources is not changed.

## 2.7 Operational environment

The system shall be implemented on a computer at IRF. The system is accessed using a web browser. Thus, to be able to access the data and models an Internet connection is necessary. There shall be two different access possibilities, a web page for registered users and another for public users. Elforsk is such a registred user. Specific data and detailed models will only be available to Elforsk.

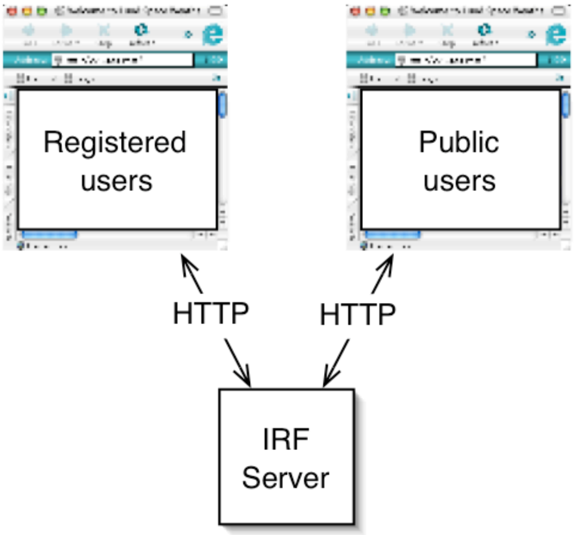


**Fig. 5.** Illustration of the operational environment.

# 3 SPECIFIC REQUIREMENTS

The specific requirements are divided into two categories: capability requirements and constraint requirements. The capability requirements describe what the user wants to do and one requirement defines an operation that the software shall be able to perform. The constraint requirements place restrictions on how the user requirements are to be met. Each requirement has a unique identifier with the following fields:

1**. CAP.** or **CON.,** capability or constraint requirement,

2. a sequential number.

## 3.1 Capability requirements

| | |
|---|---|
| **CAP.1.** | GIC prediction for one selected transformer from solar wind data. |
| Source | 2.4.7.5 |
| **CAP.2.** | Single station GIC forecast. |
| Source | 2.4.1, 2.4.6, 2.4.7.1–2.4.7.3 |
| **CAP.3.** | Single station GIC prediction. |
| Source | 2.4.1, 2.4.6, 2.4.7.1–2.4.7.3 |
| **CAP.4.** | Single station GIC cases for public access. |
| Source | 2.4.6 |
| **CAP.5.** | GIC index. |
| Source | 2.4.3 |
| **CAP.6.** | Station average GIC index. |
| Source | 2.4.7.4 |
| **CAP.7.** | Station maximum GIC index. |
| Source | 2.4.7.4 |
| **CAP.8.** | Zonal average GIC index. |
| Source | 2.4.7.4 |
| **CAP.9.** | Zonal maximum GIC index. |
| Source | 2.4.7.4 |
| **CAP.10.** | Graphical display of station values on a map of the Swedish part of NordEl. |
| Source | 2.4.5 |
| **CAP.11.** | Graphical display of zonal values on a map of the Swedish part of NordEl. |
| Source | 2.4.5 |
| **CAP.12.** | Confidence factors on prediction. |

| | |
|---|---|
| Source | 2.4.7.3 |
| **CAP.13.** | Probability of single station GIC exceeding a threshold value for different durations. |
| Source | 2.4.3 |
| **CAP.14.** | Result files for benchmarking. |
| Source | 2.4.4 |

### 3.2 Constraint requirements

| | |
|---|---|
| **CON.1.** | One hour prediction horizon. (Mandatory) |
| Source | 1.2, 2.5 |
| **CON.2.** | 95% accuracy of zonal average absolute GIC. (Goal) |
| Source | 1.2, 2.5 |
| **CON.3.** | 95% accuracy of zonal maximum absolute GIC. (Goal) |
| Source | 1.2, 2.5 |