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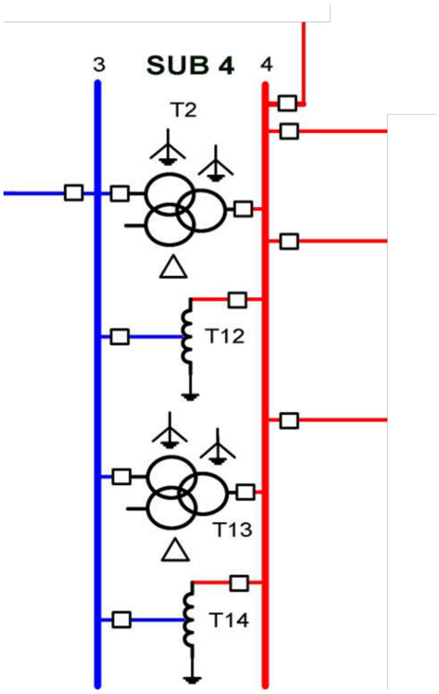
Validation of Geomagnetically Induced Current Modelling Code

Earth Hazards and Observatories Programme

Internal Report IR/17/009



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EARTH Hazards and Observatories PROGRAMME

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Front cover

Circuit diagram of a substation from Horton et al. (2012). © 2012 IEEE. Reprinted, with permission, from IEEE Transactions on Power Delivery.

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Validation of Geomagnetically Induced Current Modelling Code

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BRITISH GEOLOGICAL SURVEY

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Foreword

This report is the internally published product of a study by the British Geological Survey (BGS) in conjunction with the University of Otago, Dunedin, New Zealand on the modelling of Geomagnetically Induced Currents (GICs) in grounded high-voltage power networks.

Summary

A paper by Horton et al. (2012) details a test grid containing 8 substations with 15 transformers connected by 15 lines. The paper gives detailed information about location, resistances and connections including features such as capacitors, delta and composite transformer types. The model output for 1 V/km in the north-south and east-west directions are provided. In early 2017, the BGS Geomagnetism team produced an equivalent model using the Nodal Admittance Method and proved their model to be consistent with Horton et al. This report outlines our approach and results.

Acknowledgements

We wish to acknowledge the help of the following individuals who have contributed to the project:

Prof Craig Rodgers (University of Otago) and Dr David Boteler (Natural Resources Canada).

In particular we wish to acknowledge the help of Dr Tim Divett, a post-doctoral researcher at the University of Otago, who was very generous with his time and ideas for representing and modelling the Horton grid.

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1 Introduction

Modelling of Geomagnetically Induced Currents has been ongoing in BGS since the early 2000s. The problem consists of the geophysical step whereby magnetic field variations are converted into expected electric field variation in the ground with respect to a conductivity model of the subsurface. The engineering step involves modelling a connected high-voltage grid with a number of transformers and connecting lines with given resistances both of the lines and the transformers and their earthing points.

The UK's high-voltage system as run by National Grid has been modelled a number of times by Allan McKay, Katie Turnbull and more recently in 2012-2014 by Ciaran Beggan, Gemma Kelly and the FP7 EURISGIC project (by Magnus Wik and Ari Viljanen). This grid has typically consisted of an approximation of a single node connected by one or more lines to other nodes within the UK. The model has become more complex over time, starting as a relatively simple model of the Scottish Power Midland Valley network (McKay, 2003), then a UK wide network (Turnbull, 2011) with around 250 nodes and then a more complex version of the UK network (Beggan et al., 2013) with almost 700 nodes. The EURISGIC model is comparable to the Turnbull model with around 250 nodes.

As our models have increased in complexity, it has become more difficult to correctly determine if the network is being reliably captured. Some tests can be made to check if the GIC values are consistent (e.g. zero sum GIC) but mistakes occur even in very careful modelling and lack of information about the precise nature of the network means it is difficult to be certain that the values modelled are correct. Even more importantly, few GIC measurements are available to validate the models, leaving much of the later modelling as educated guesswork, though some of the earlier work has been validated.

The next phase of GIC modelling is pushing forwards from large scale nodes or substation level into the transformer level within larger substations. There are typically several transformers at most substations, stepping up or down the voltage as required. The additional complexity has been ignored to a large extent as the lack of information and a viable technique for capturing this level of detail has not been developed in BGS.

Recently, in conjunction with a collaboration with the University of Otago in New Zealand, a fresh impetus has arisen to fully understand how to model GIC at transformer level. In New Zealand the project team have access to a long-term 'GIC' dataset and detailed information about the network model of the South Island. Tim Divett has been working on understanding and modelling transformers on an individual level. Using the work of Boteler and Pirjola (2014, in particular) the ability to represent a number of transformers in an equivalent manner to single substation has been developed.

In order to test this, the network model of Horton et al. (2012) is used to verify the technique and the GIC flowing through this system. In the next few sections, we detail the text network, how it is represented and compare it to the results in the Horton et al paper. We discuss some of the issues and pitfalls.

2 Description of the test network:

The Horton et al. (2012) network (hereafter Horton network) consists of 8 substations, 15 transformers and 15 line connections, at either 345 or 500 kV. The circuit has high-voltage (HV) and low-voltage (LV) buses with multiple connections to most, and includes both conventional transformers and autotransformers. In addition, there are series and neutral connected GIC blocking devices (capacitors), one on the line connecting substation 5 to switching station 7 and one in the neutral of substation 1 (T1). The circuit/network outline is shown below in Figure 1.

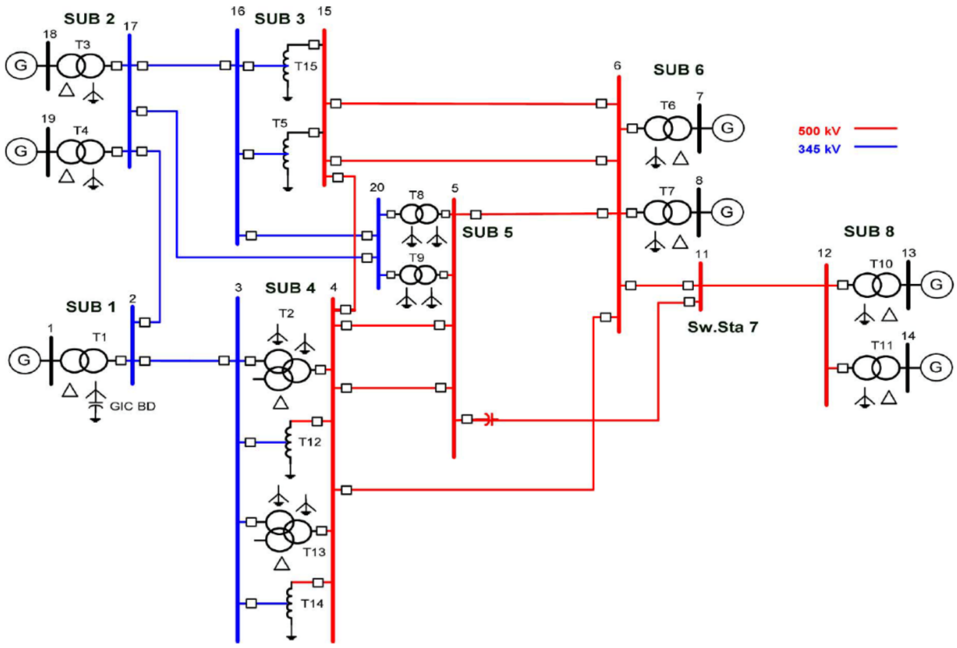

Figure 1: Network diagram of Horton et al (2012) grid. Blue: LV lines; Red: HV lines. Note the GIC blocking capacitors on Line 4-11 and on T1. © 2012 IEEE. Reprinted, with permission, from IEEE Transactions on Power Delivery.

The substations are notionally placed in south-eastern North America centred around Kentucky and cover an area of around 6 degrees in longitude by 2 degrees in latitude (around 600 km x 200 km). The paper gives three tables of information regarding the earthing and transformer resistances of the HV and LV buses and of the individual lines. The latitude and longitude are also provided so as to compute the line lengths.

Figure 1 comprises of five main types of substation:

- Substation 3 contains two autotransformers with a HV and LV bus
- Station 5 contains two conventional transformers with a HV and LV bus
- Station 4 is a combination of substation 3 and 5 (two autotransformers, two conventional transformers) with a HV and LV bus
- Stations 1, 2, 6 and 8 are conventional transformers with a HV/LV bus on one side and a grounded bus on the other.
- Station 7 has no transformers or earthing point and is essentially a line split.

We will describe how to model each of these types in the next few sections. The line resistances and transformer data for the system are given in Tables II and III of Horton et al.

3 Modelling Substations and Individual Transformers

3.1 CONVENTIONAL TRANSFORMERS: SUBSTATION 5

Substation 5 consists of two conventional transformers, with a HV side and a LV side and multiple lines leaving on both buses. To capture the detail in this substation, we model the two buses (HV/LV) as nodes with infinite resistance to ground and a connecting node with the substation earthing resistance (in this case, 0.1 Ohm). The HV resistances for T8 and T9 are given as 0.04 Ohm/phase and for the LV resistances are 0.06 Ohm/phase.

The transformers T8 and T9 can now be considered as lines connecting the two buses and the virtual earthing node in the centre. The connections to the other substations then emanate from the buses.

Figure 2 shows pictorially how to represent the HV and LV buses and the T8 and T9 transformers as lines with a known resistance. They all connect via the virtual node with 0.1 Ohm resistance.

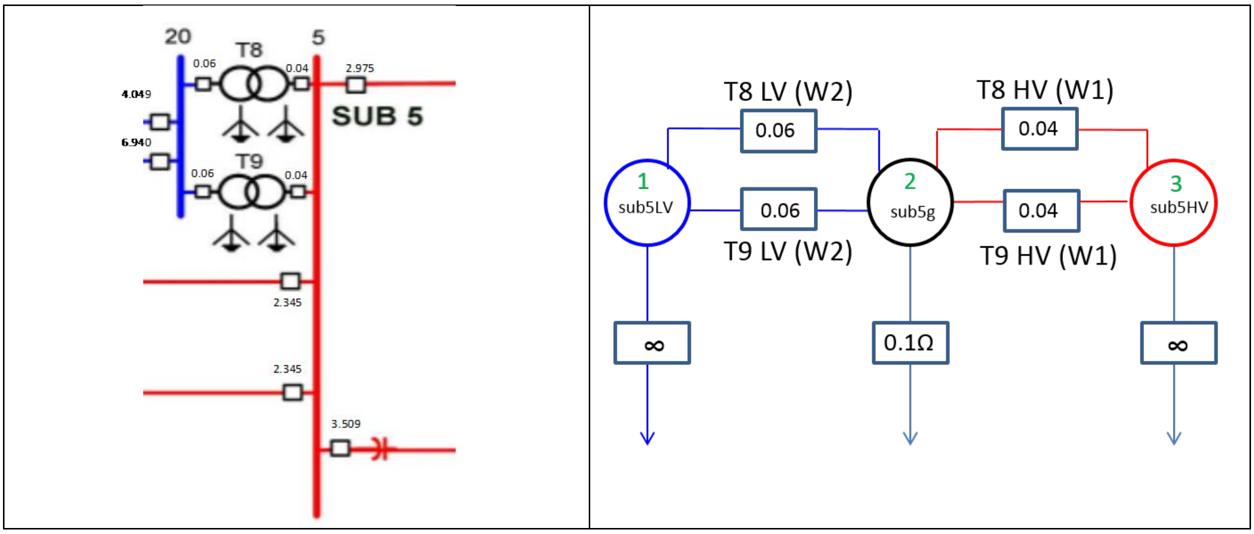

Figure 2: Representation of Substation 5. Left: as a circuit diagram. Right: as a set of virtual nodes with the transformers being connecting lines between the buses.

This representation allows us to write down the buses as a set of node locations and the transformers as a series of lines connecting them to the virtual node.

The current setup of the GIC modelling code is heavily based on how Katie Turnbull set up her UK network and so follows the same file format conventions In particular, it sets out the numbers of node and transformers in the first two lines, then the numbering and location of the transformers, then it describes the line connections between transformers. The transformers must be listed in numerically increasing order from 1 to N, where N is the number of transformers. There are then columns for the other relevant information about the transformer.

Number	Latitude	Longitude	Earthing Resistance	Transformer Resistance
1	32.7051	-84.6634	Inf	Inf
2	32.7051	-84.6634	0.1	0
3	32.7051	-84.6634	Inf	Inf

Table 1: Representation of Substation 5 transformer nodes

Table 1 shows the location and resistances of the nodes labelled in Figure 2. Note the virtual node (#2) has zero transformer resistance but has an earthing resistance of 0.1 Ohm.

The connections within the substation are then represented in Table 2. Line voltage is set to zero to distinguish it as within a substation.

Node From	Node To	Line Resistance	Is Transformer	Dummy column	Line Voltage
1	2	0.06	1	Inf	0
1	2	0.06	1	Inf	0
2	3	0.04	1	Inf	0
2	3	0.04	1	Inf	0

Table 2: Representation of node connections in Substation 5

3.2 AUTOTRANSFORMERS: SUBSTATION 3

Substation 3 consists of two autotransformers, with a HV side and a LV side and multiple lines leaving on both buses. To capture the detail in this substation, we model the two buses (HV/LW) as nodes with infinite resistances to ground and a connecting node with the substation earthing resistance (in this case, 0.2 Ohm). The HV resistances for T15 and T5 are given as 0.04 Ohm/phase and for the LV resistances are 0.06 Ohm/phase. The difference with the representation of Substation 5 is that the HV and LV connect in series and then onto the virtual node which is grounded as in Figure 3.

The representation in the file format for the internal connections are shown in Table 3 and Table 4.

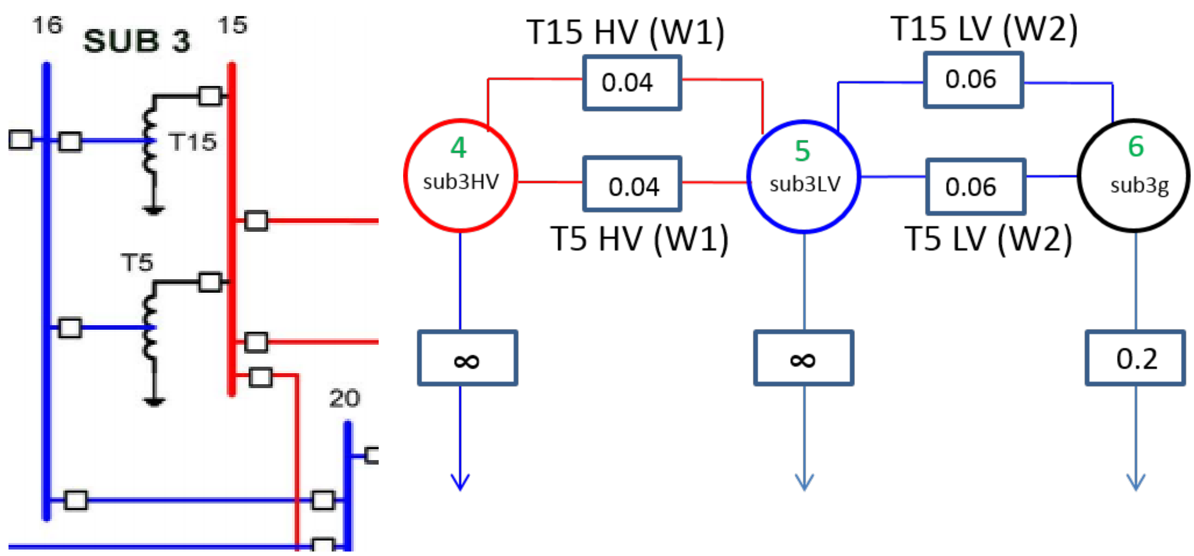

Figure 3: Representation of the autotransformers in Substation 3. Left: as a circuit diagram. Right: as a set of virtual nodes with the transformers being connecting lines between the buses.

Number	Latitude	Longitude	Earthing Resistance	Transformer Resistance

4	33.9551	-84.6794	Inf	Inf
5	33.9551	-84.6794	Inf	Inf
6	33.9551	-84.6794	0.2	0

Table 3: Representation of Substation 3 transformer nodes

The connections within the substation are then represented in Table 2. Line voltage is set to zero to distinguish it as within a substation.

Node From	Node To	Line Resistance	Is Transformer	Dummy column	Line Voltage
4	5	0.04	1	Inf	0
4	5	0.04	1	Inf	0
5	6	0.06	1	Inf	0
5	6	0.06	1	Inf	0

Table 4: Representation of node connections in Substation 3

Finally, from the overall circuit diagram we can see that node 1 (at substation 5) in our labelling system is connected to node 5 (substation 3) on the LV side (345 kV). This is an actual connection, so has a line resistance and a line voltage value. This can be represented as follows in Table 5.

Node From	Node To	Line Resistance	Is Transformer	Dummy column	Line Voltage
1	5	4.049	NaN	Inf	345

Table 5: Line connection between Bus 1 and Bus 5.

3.3 EDGE NODES: SUBSTATION 2

The edge nodes such as Substation 2, 6 and 8 are essentially half of the Substation 5 representation, as they only have a single side (HV or LV) and a grounded point. These can be represented either a single or double set of transformers in parallel to the grounding node. Substation 2 is shown here as an example in Figure 4 and Table 6 and Table 7.

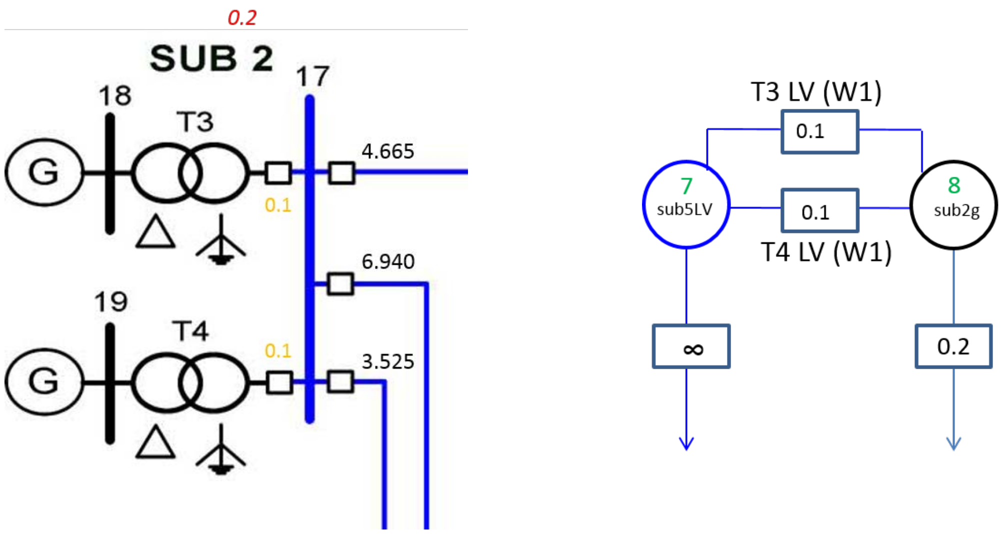

Figure 4: Representation of the edge transformers in Substation 2. Left: as a circuit diagram. Right: as a set of virtual nodes with the transformers being connecting lines between the bus and ground.

Number	Latitude	Longitude	Earthing Resistance	Transformer Resistance
7	34.3104	-86.3658	Inf	Inf
8	34.3104	-86.3658	0.2	0

Table 6: Representation of Substation 2 transformer nodes

Node From	Node To	Line Resistance	Is Transformer	Dummy column	Line Voltage
7	8	0.1	1	Inf	0
7	8	0.1	1	Inf	0

Table 7: Representation of node connections in Substation 2.

Note, that Substation 1 is a special case, as it has only one transformer with a GIC blocking device. In this case the connection has an Inf(inite) grounding resistance (not 0.2 Ohm as might be suggested from Table III in Horton et al.).

3.4 MIXED TRANSFORMERS: SUBSTATION 4

Substation 4 has two autotransformers and two conventional transformers in parallel together. In this case, there is still a single grounding node through which the current flows. From Figure 2 we see that the virtual node is between the HV and LV buses, but in Figure 3 the virtual node is at the right-hand side of the diagram. The simplest way to connect the two types of transformers via the virtual node is shown in Figure 5.

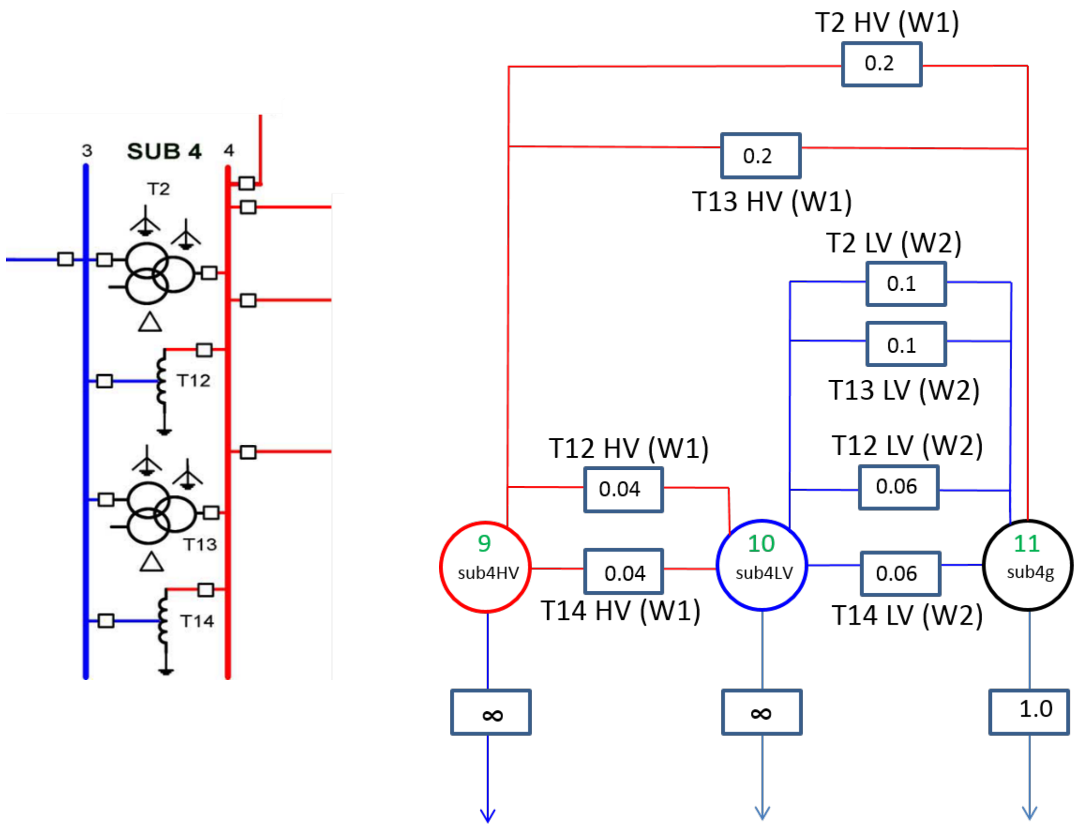

Figure 5: Representation of the edge transformers in Substation 4. Left: as a circuit diagram. Right: as a set of virtual nodes with the transformers being connecting lines between the bus and ground.

This is a more complicated substation, with 3 nodes (Table 8) but 8 connections internally (Table 9).

Number	Latitude	Longitude	Earthing Resistance	Transformer Resistance
9	33.5479	-86.0746	Inf	Inf
10	33.5479	-86.0746	Inf	Inf
11	33.5479	-86.0746	1.0	0

Table 8: Representation of Substation 4 transformer nodes

Node From	Node To	Line Resistance	Is Transformer	Dummy column	Line Voltage
9	11	0.06	1	Inf	0
9	11	0.06	1	Inf	0
9	11	0.1	1	Inf	0
9	11	0.1	1	Inf	0
10	11	0.2	1	Inf	0
10	11	0.2	1	Inf	0
9	10	0.04	1	Inf	0
9	10	0.04	1	Inf	0

Table 9: Representation of node connections in Substation 4.

3.5 RELABELLING AND RENUMBERING THE HORTON GRID

The above set of examples started at number 1 to 11 for convenience sake, but in order to correctly represent the buses and virtual node within the Horton grid we must relabel them in ascending order. The Horton grid is missing buses 9 and 10 (reason unknown, D. Boteler, pers. comm., Feb 2017) presumably due to various iterations during its development. It also does not use virtual nodes as we do. Figure 6 shows the relabelling with yellow boxes being buses and orange being the virtual nodes, running from 1 to 18.

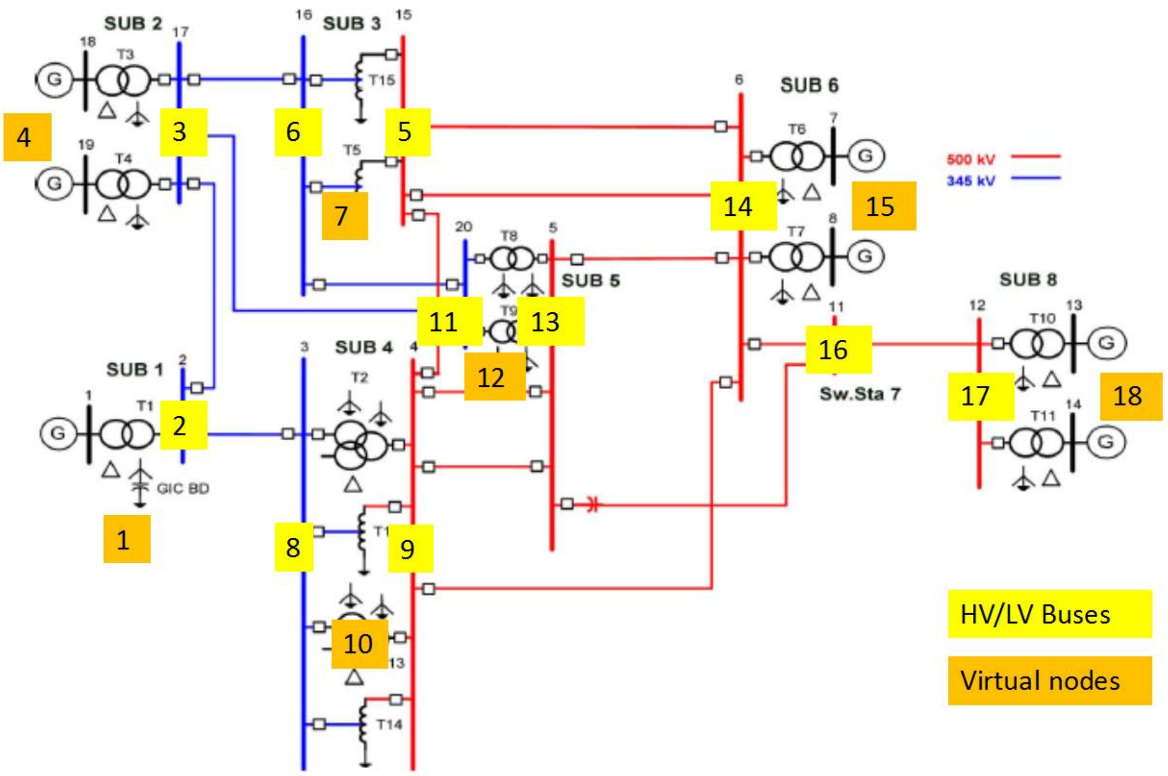

Figure 6: Relabelled buses and virtual nodes of the Horton grid for use in the GIC code

The final grid contains 18 transformers and 38 connections as shown in Table 10.

18	NaN	NaN	NaN	NaN	NaN
38	NaN	NaN	NaN	NaN	NaN
1	33.6135	-87.3737	0.2	Inf	NaN
2	33.6135	-87.3737	Inf	Inf	NaN
3	34.3104	-86.3658	Inf	Inf	NaN
4	34.3104	-86.3658	0.2	0	NaN
5	33.9551	-84.6794	Inf	Inf	NaN
6	33.9551	-84.6794	Inf	Inf	NaN
7	33.9551	-84.6794	0.2	0	NaN
8	33.5479	-86.0746	Inf	Inf	NaN
9	33.5479	-86.0746	Inf	Inf	NaN
10	33.5479	-86.0746	1	0	NaN
11	32.7051	-84.6634	Inf	Inf	NaN
12	32.7051	-84.6634	0.1	0	NaN
13	32.7051	-84.6634	Inf	Inf	NaN
14	33.3773	-82.6188	Inf	Inf	NaN
15	33.3773	-82.6188	0.1	0	NaN
16	34.2522	-82.8363	Inf	0	NaN
17	34.1956	-81.098	Inf	Inf	NaN
18	34.1956	-81.098	0.1	0	NaN
1	2	0.1	1	Inf	0
2	3	3.525	NaN	Inf	345
3	4	0.1	1	Inf	0
3	4	0.1	1	Inf	0
3	6	4.665	NaN	Inf	345
3	11	6.94	NaN	Inf	345
5	6	0.04	1	Inf	0
5	6	0.04	1	Inf	0
6	7	0.06	1	Inf	0
6	7	0.06	1	Inf	0
6	11	4.049	NaN	Inf	345
8	10	0.06	1	Inf	0
8	10	0.06	1	Inf	0

8	10	0.1		1	Inf	0
8	10	0.1		1	Inf	0
9	10	0.2		1	Inf	0
9	10	0.2		1	Inf	0
9	8	0.04		1	Inf	0
9	8	0.04		1	Inf	0
9	14	4.666	NaN		Inf	500
9	13	2.345	NaN		Inf	500
9	13	2.345	NaN		Inf	500
5	9	1.986	NaN		Inf	500
2	8	3.512	NaN		Inf	345
11	12	0.06		1	Inf	0
11	12	0.06		1	Inf	0
13	12	0.04		1	Inf	0
13	12	0.04		1	Inf	0
14	15	0.15		1	Inf	0
14	15	0.15		1	Inf	0
14	16	1.444	NaN		Inf	500
5	14	2.924	NaN		Inf	500
5	14	2.924	NaN		Inf	500
13	14	2.975	NaN		Inf	500
13	16	Inf	NaN		Inf	500
17	18	0.1		1	Inf	0
17	18	0.1		1	Inf	0
16	17	2.324	NaN		Inf	500

Table 10: Full representation of the Horton grid. Nodes are highlighted in light orange; connections are in light grey.

4 Comparison of simulated GIC flows in the Horton grid

Before going to the comparison of our simulations compared to the Horton grid, there are a couple of points to note about this grid which are important to getting to the correct result. Firstly, there are a number of parallel lines e.g. buses 5 to 14. Tim Divett has updated the Matlab code to handle parallel lines and Gemma Kelly has done likewise for the Python code. Secondly, the length of the lines between substations in the Horton grid have been extended by 3% to account for line sag and non-straight lines. We have not added this feature into our code, though have checked we can do this. There is a capacitor placed on the connection substations 5 and 7 (buses 13 to 16). This is modelled as an Inf resistance. Finally, both the line and the transformer resistances are given in Ohms per phase, so must be divided by 3 to get the correct GIC values.

A voltage of 1 V/km was imposed in the north-south and east-west directions. The Horton paper gives tables of the computed voltages along the lines as well as the substation total GIC and the GIC per transformer. We give the Horton values from the paper in comparison to the output from the Matlab and Python codes. While the values are not an exact match, they are extremely close and we account for the < 1 A differences as being due to the difference in line lengths and computational differences e.g. in the method for interpolation and the fact that we use the Nodal Admittance Method. Although Horton et al. claim the results were independently verified by all five authors, it is likely they found similar differences and averaged their results.

4.1 GIC PER SUBSTATION

The results per substation are given in Table 11. The root-mean-square differences is 2.3 A for the North direction and 0.7 A for the East direction for the Python code; the differences are slightly larger at 3.5 A and 1 A respectively for the Matlab code. The main contributor is the differences in the GIC for Substation 6 with a northwards electric field, which is -57.29 A versus -53.24 A and 52.88 A in our implementation. The Horton et al. (2012) values are extracted from their Table VII.

The sum of the GIC values is zero, as it should be.

	Horton et al. (2012)		Python		Matlab	
	North	*East*	*North*	*East*	*North*	*East*
Sub1	0.00	0.00	0.00	0.00	0.00	0.00
Sub2	115.63	-189.29	114.25	-189.77	113.35	-188.95
Sub3	139.85	-109.49	137.87	-109.79	136.80	-109.32
Sub4	19.98	-124.58	19.22	-124.63	19.06	-124.11
Sub5	-279.08	-65.46	-280.55	-63.94	-278.49	-63.42
Sub6	-57.29	354.52	-53.24	353.99	-52.88	352.39
Sub7	0.00	0.00	0.00	0.00	0.00	0.00
Sub8	60.90	134.30	62.45	134.14	62.15	133.42

Table 11: Comparison of Total GIC per substation from Horton et al and the two different code sets (Python and Matlab).

4.2 GIC PER TRANSFORMER

The GIC per transformer can also be extracted directly or computed from the values on the buses. Table 12 shows the output from the Horton paper compared to the GIC computed from the buses (computed in Python) and the GIC extracted directly from the computation in Matlab. The Horton et al. (2012) values are extract from their Table VIII.

Note, care must be taken to extract these values, as they have to be matched up correctly to the correct side of the transformers. Nearly all the differences are less than 1 A per phase.

		Horton et al. (2012)		Python		Matlab	
	Voltage	*North*	*East*	*North*	*East*	*North*	*East*
T1	HV	0	0	0.00	0.00	0.00	0.00
T2	HV	1.75	-6.94	1.70	-6.95	0.93	-8.61
	LV	0.59	-5.18	0.75	-6.91	0.56	-5.16
T3	HV	19.27	-31.55	19.04	-31.63	18.89	-31.49
T4	HV	19.27	-31.55	19.04	-31.63	18.89	-31.49
T5	series	18.09	-34.89	17.54	-34.96	17.35	-34.80
	common	23.31	-18.25	22.98	-18.30	22.80	-18.22
T6	HV	-9.55	59.09	-8.87	59.00	-8.81	58.73
T7	HV	-9.55	59.09	-8.87	59.00	-8.81	58.73
T8	HV	-27.67	-17.89	-27.89	-17.68	-27.64	-17.58
	LV	-18.84	6.98	-18.87	7.02	-18.77	7.01
T9	HV	-27.67	-17.89	-27.89	-17.68	-27.64	-17.58
	LV	-18.84	6.98	-18.87	7.02	-18.77	7.01
T10	HV	10.15	22.38	10.41	22.36	10.35	22.24
T11	HV	10.15	22.38	10.41	22.36	10.35	22.24
T12	Series	7.24	-21.75	7.11	-21.77	7.06	-21.67
	common	0.99	-8.64	0.75	-6.91	0.93	-8.61
T13	HV	1.75	-6.94	1.70	-6.95	1.69	-6.92
	LV	0.59	5.18	0.75	-6.91	0.56	-5.16
T14	series	7.24	-21.75	7.11	-21.77	7.06	-21.67
	common	0.99	-8.64	0.75	-6.91	0.93	-8.61
T15	series	18.09	-34.89	17.54	-34.96	17.35	-34.80
	common	23.31	-18.25	22.98	-18.30	22.80	-18.22

Table 12: Per transformer GIC (Amps/phase)

5 Conclusions

This report covers the method for coding and analysing the Horton et al. (2012) test grid. Two implementations of the code in Python and Matlab were tested and found to be consistent to within the expected computation and implementation differences. The values are also consistent with the Horton grid results to within less than 1 A per phase for the transformers and less than 2 A RMS for the total GIC per substation.

Thus, we have verified and validated the code, our representation of the models and our ability to correctly extract the GIC values. This result and the understanding gained in its implementation allows us to confidently model sophisticated grid models, assuming that the necessary information about the networks is available.

Glossary

Geomagnetically Induced Currents Currents arising in the conductive ground created by the time-varying magnetic field during geomagnetic storms.

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

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