Reduction of Geomagnetically Induced Current Impacts by Optimized Neutral Point Connections

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Abstract

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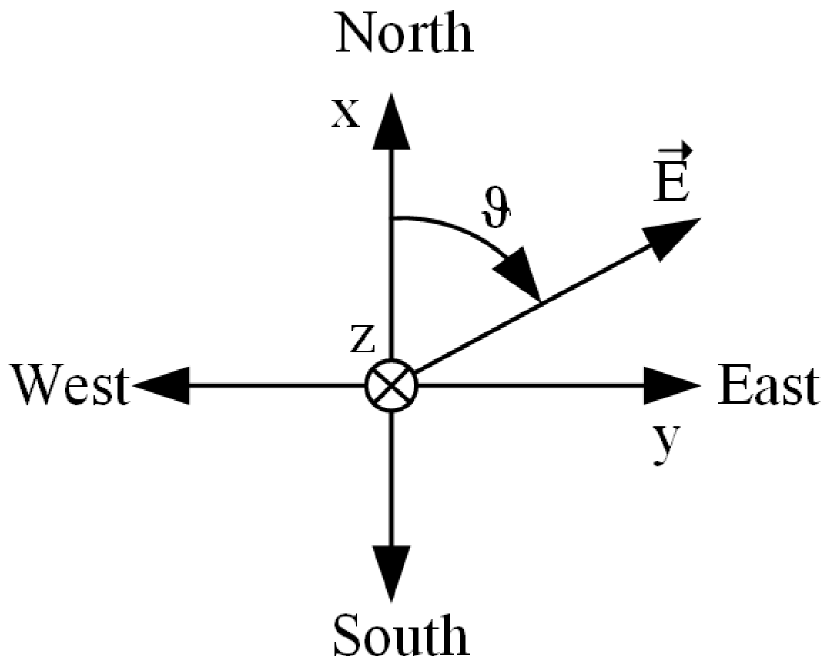

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Reduction of Geomagnetically Induced Current Impacts by Optimized Neutral Point Connections

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Abstract: Solar storms impact electrical power grids by causing DC neutral point currents in transformers. These currents lead to half-cycle saturation as well as other related and unwanted effects in the grid. To reduce the effect of these currents on the grid, DC-blocking devices can be installed or changes in the grid topology can be made. However, these counter measures often have unwanted side effects or cannot be applied to the grid due to operational restrictions. In this work, a novel mitigation approach, based on the distribution of currents on more transformers, is presented. The number and location of grounded transformer neutral points is optimized, taking grid related constraints such as the minimal number of transformer connections into account. It is shown that the algorithm can effectively reduce the stress on transformers without any additional assets and thus increase system security.

1 Introduction

Geomagnetically induced currents (GICs) are the result of changes in the Earth's magnetic field, caused by interacting with the solar wind. The magnetic field change results in an induced electric field in the Earth's conductive surface. Conductive infrastructure which is connected to the ground, such as the transmission grid or pipelines, provides a low resistive path for these currents [1]. In the case of power grids, GICs enter through grounded transformer neutral points. The frequency range of GICs is lower than 0.1 Hz [2] and compared to the grid operating frequency of 50 or 60 Hz, GICs behave like DC. GICs lead to half-cycle saturation of transformers, causing internal temperature hot spots, harmonic emissions and higher reactive power demand. As these currents and their effects on transformers can lead to serious damages in the grid, was the case in the Hydro-Quebec Blackout in 1989 [3, 4] or the Malmö Blackout in 2003 [5], the calculation of GICs and the development of mitigation strategies have become an important aspect for power grid safety.
There are other sources in the grid which also result in DC neutral point currents, e.g., public transportation systems [6, 7], recurring switching actions[6], galvanic coupling from cathodic corrosion protection[8] or coupling in AC/DC hydrid lines[9]; however, the magnitudes are lower than those of GICs.

For GIC calculations, the LFC Simulator [10] is used. This software has two different options for calculations: Either load the magnetic field data and calculate an induced electric field or directly enter an electric field with magnitude and direction. The first calculation method assumes the magnetic field as a plane wave, which penetrates into the ground and induces an electric field in the Earth's conductive surface [11]. With the electric field, regardless of either method on or two is used, GICs in every transformer and line can be calculated. For this purpose, a voltage source, which is dependent on the location and distance to a reference node, can be placed between the substation grounding system and remote earth. The magnitude of the voltage sources is calculated with the electric field times the distance between these two points. This is called the Nodal Admittance Matrix method [7]. As described by [12], this is equivalent to the well-known Lehtinen-Pirjola method and was proofed with real measurements in [7, 13, 14].

The result of the GIC calculation shows transformers which are highly influenced by geomagnetic variations. If currents exceed certain limits, the GICs need to be reduced to prevent damage to assets and to provide a safe and reliable electricity supply. Additional active and passive electrical components can be used to reduce or mitigate the negative effects caused by GICs. There are six main known categories of GIC mitigation and blocking techniques, each with advantages and disadvantages:

- Elimination of neutral connections
- Blocking devices in neutral connections
- Blocking devices along transmission lines
- DC Diverters
- DC-compensated transformers
- Corrective line switching

The method of neutral point eliminations pursues the approach to eliminate the path for GICs by operating lines with only one neutral point at one side of the line [15]. This is achieved by changing the transformer topology from a typical wye-wye connection to delta-wye or by disconnecting the neutral point. If the line is only a point-to-point connection, this means that there is no path for the GIC to flow through the grid. However, this method has several flaws. The phase shift introduced by delta connections adds more complexity to interconnected grids[15]. In addition to the costs of new transformers with this vector group, this topology can lead to overvoltages during faults and damage assets.

The installation of additional devices in neutral points to block high GICs is the most common mitigation approach. The devices can be, e.g., capacitors [3, 16–18], in which the blocking element is bypassed with switches during normal operation and block the DC-behavior of GICs during solar storms. Such devices are standardized in [19]. Resistors in neutral points increase the resistance for GICs and reduce the magnitude of neutral point currents. These resistors can be static, variable [20–22] or even variable with a central optimized controller [23].
More recent developments use converter-based devices that, e.g., use a buck-boost converter to create a counteracting voltage in the neutral point [24]. These devices can also be utilized to work in grid-supporting mode during geomagnetic inactive times. Furthermore, the combination of DC blocking devices with harmonic suppression systems is under research [25].

Another approach with power electronics is the implementation of fast semiconductor switch in neutral points. Compared to other capacitor-based solutions, this device with switching frequencies of 1.2 kHz proposes a reduction of the GIC influence on transformers by fast switching the neutral point, with no change in short-circuit behavior at the same time [26].
The placement of these neutral blocking devices is not trivial and can lead to even more disturbances [27]. However, there are optimization algorithms that propose an optimal placement [28–31].

The placement of mitigation devices along or in series with transmission lines is another way to mitigate the effect of GICs. The devices can be variable series resistances with capacitors, which are proposed so as to not influence normal operation [32], or capacitors in series [33]. The flow of GICs on single lines can be reduced with these in series connected devices. However, this may lead to disturbances in the grid during normal operation. Additionally, the GIC may distribute differently and lead to disturbances on other lines in a connected power grid.

DC-diverters, or grounding transformers, are special shunt transformers that are connected in substations to reduce the GIC stress on power transformers. The DC-diverter has a lower resistance than the transformer under protection. The GIC splits between the diverter and the transformer, whereby most of the GIC flows through the diverter and therefore reduces the GIC stress on parallel transformers. [34, 35] However, the costs of DC-diverters are tremendous and there is no implementation thereof known to the authors.

Direct current compensation systems (DCC) in transformers mitigate the effect of DC with a counteracting current through an additional winding [36]. This compensation current creates a direct flux with the opposite sign of the flux resulting from the neutral point current. For this purpose, a field sensor measures the flux in the transformer core. The counteracting flux mitigates/cancels the direct flux in the core and thus the half-cycle saturation effects. The GIC still flows through the transformer and only the effect is canceled. At the moment DCCs are capable of reducing the direct flux of a few ampere in the transformer neutral. They are mainly used to reduce the transformer audible sound during geomagnetic quiet times.

The approach to switch lines and therefore change the connections between substations was pursued by [37–39]. While [37] optimizes the grid connections to reduce the reactive power loss on transformers [38], models the AC load flow with additional reactive power losses of transformers and minimizes the costs of load shedding and generation dispatch needed after a corrective line switching. However, due to grid operation, high load flows or n-1 security it may not always be possible to shut down lines to reduce the impact of solar storms.

The mitigation algorithm proposed in this article is also a kind of corrective switching, but does not change the line configuration. Instead, it optimizes the number and location of connected neutral points in the grid. There are no additional assets needed and load flows are not affected.

2 Description of the Proposed Method

The AC transmission grid in Europe with 220 kV and 380 kV voltage levels is solidly grounded. The reasons are e.g. fast detection of phase-to-ground faults, fast fault clearing times and preventing overvoltages during faults. However, not every transformer neutral point is connected. The number of connected transformer neutral points is determined by the minimum and maximum single phase-to-ground fault currents. The minimal current is needed for a safe and reliable fault detection and fault clearance. The maximum fault currents must stay within limits of the short circuit current ratings of all assets in the grid and prevent damage on assets and extreme touch-voltages. This leads to the commonly applied rule that only one neutral point per voltage level is grounded in a substation. If there are two 380/220 kV transformers operating in parallel in one substation, the 380 kV neutral point of one transformer and the 220 kV neutral point of the other transformer are solidly grounded. This also prevents the transmission of a zero sequence system through the transformer from one voltage level to another. This operation mode means, that there are neutral points in the grid which are not used in geomagnetic quiet times, but can be utilized during a solar storm for additional temporary connections. The proposed GIC mitigation method uses these available neutral points to distribute the currents on more transformers, thereby reducing the GIC-load on single transformers. To find the best neutral point configuration, an optimization problem is formulated and solved.
Before an objective function can be formulated, a goal of the mitigation approach must be defined. A possible mitigation approach would be to reduce the maximum transformer current in the grid or to reduce GICs at transformers which are more vulnerable to DC neutral currents, e.g., three phase, five limb transformers. In this article, the selected approach is to minimize the overall GIC impact on the grid.

$$minimize \sum_{n=1}^{N_T} \mathbf{I}_{Tn}^2(\mathbf{np}) \tag{1}$$

The objective function in (1) minimizes the sum of all squared transformer currents I_{Tn} in p.u. of the nominal phase current, where n is the transformer index and $\mathbf{np}$ describes the actual neutral point status. The actual transformer currents depend on both the electric field (magnitude and orientation) and the grid topology. As the electric field is held constant during the optimization and only the neutral point connections in the grid are changed, the transformer currents are only dependent on the optimization variable np. If the electric field changes, the optimization must be done again. The relation between transformer currents and neutral point connections is complex: An additional parallel transformer means a split of the transformer currents on the one hand; on the other hand, the parallel resistance reduces the overall resistance of the grid.

According to Kirchhoff's law, the total sum of all transformer currents in the simulated grid is zero. Therefore, only the absolute currents or the squared currents can be minimized. Because of the squaring in the objective function, higher currents are more penalized than lower currents. Therefore a maximum current reduction is indirectly included.

The optimization variable and constraints that need to be taken into account are the following:
As described in (2), the optimization variable $\mathbf{np}$ is a binary vector with the size $N_N \times 1$, where N_N is the number of disposable neutral points in the grid, and defines whether a neutral point i is connected ($np_i = 1$) or if it is disconnected ($np_i = 0$) to the ground.

$$\mathbf{np}_i \in \{0, 1\}, i = 1, ..., N_N \tag{2}$$

The neutral point connection vector np is added in the GIC calculation described in [7] and multiplied with the winding resistances of the related transformer in the branch-node matrix.

From a grid-operator's point of view, only a limited number of changes in the grid topology is applicable in practice. To limit the number of allowed changes, this constraint is mathematically introduced with (3). This constraint compares the original neutral point connection vector $\mathbf{np}_0$ with the optimization variable $\mathbf{np}$ through an exclusive 'or' and calculates the sum. The sum must be lower or equal to an arbitrarily defined number of allowed switching actions $npc_{\max}$.

$$\sum_{n=1}^{N_N} (np_{0i} \oplus np_i) \leq npc_{\max} \tag{3}$$

To limit the maximum current of transformers, constraint (4) is introduced. The maximum current $I_{T,max}$ can be either set as a global maximum for all transformers or as an individual maximum of each transformer. With individual limits, different transformer core types can be taken into account and particular attention to vulnerable types can be paid. The assessment of tolerable maximum currents does not fall within the scope of this article. More details on transformer current limits to prevent hot spots, harmonic emissions or reactive power demand can be found in the literature, e.g.,[40, 41].

$$|I_{Tn}| \leq I_{T,max}, n = 1, ..., N_T \tag{4}$$

As mentioned above, it is mandatory to have at least one neutral point per substation and voltage level connected to the ground. This can be accomplished in a number of ways, such as implementing a constraint for each substation that examines each neutral connection or various summation techniques.

The result of this optimization problem is an optimum neutral point connections set for the grid under investigation. As the neutral point configuration has direct influence on the magnitude of line-to-ground fault currents, short circuit calculations are needed to check for minimum and maximum fault currents. As the mitigation approach follows a modular approach, this is done outside the LFC-simulator in other power calculation software used by the grid operator. Some of the proposed changes in the grid topology may not be feasible due to the afore mentioned restrictions Therefore the optimization also generates alternative solutions close to the optimum.

The formulation of this problem shows that it is a mixed integer, nonlinear problem, due to the inverse admittance matrix used by the GIC calculation [7]. To solve this optimization problem, a genetic algorithm is used. Genetic algorithms, developed by [42], are based on the mechanics of natural selection, starting with an initial population and changing it through crossover and mutation into a new generation [43]. Especially in complex problems or problems with several local optima, these stochastic search algorithms provide good results [44]. In the described problem, the initial population is the original neutral point connection vector $\mathbf{np}_0$. The preferences on mutation rate, population size, etc. will not be further discussed in this article.

3 Application on a Test Grid

3.1 Description of the Test Grid

The proposed mitigation algorithm has been tested on the GIC-test grid from [45]. It consists of 8 substations, connected with 500 kV and 345 kV lines, 15 transformers and 19 transformer neutral points. Originally, all neutral points are connected to the ground. As described in Section 2, usually only one neutral point per voltage level and substation is grounded. Additionally, the neutral points of auto-transformers are always connected. Applied to the benchmark grid in Figure 1, this leads to the ground connected neutral points marked in green. As there is no detailed data about the rated power, nor the number of limbs of the transformers in the grid given, all GSU transformers are assumed be the same type and all other transformers have the same rated power.

Upon first considerations, a constant electric field with $E_x = 1\ \mathrm{V/km}$ and $E_y = 1\ \mathrm{V/km}$ is applied to the grid. Transformed into a polar coordinate system in Figure 2, this refers to an angle of $\vartheta = 45°$.

3.2 Influence of Neutral Point Changes

The result of the objective function highly depends on the number of allowed neutral point changes $npc_{\max}$ in the optimization variable np. The optimum results of one neutral point change ($npc_{\max}$ = 1) is shown in orange and two neutral point changes ($npc_{\max}$ = 2) in yellow in Figure 3. The shown transformer currents are calculated in p.u. of the rated current.

The original currents of each transformer, split in HV and LV winding currents, are shown in blue and the currents after the optimization are shown in orange ($npc_{\max}$ = 1), and yellow ($npc_{\max}$ = 2), respectively. The resulting objective function values are also given in Figure 3. The newly connected neutral point is $T6_{\mathrm{HV}}$ in substation 6, which operates in parallel to transformer $T7$. As several transformer neutral points are not connected, currents in the respective transformers windings are zero, e.g., $T2_{\mathrm{HV}}$. Although the neutral point of $T1$ in substation 1 is connected, there is no current flowing through this transformer, as a GIC blocking device is installed there. As mentioned beforehand, splitting the neutral current of one transformer onto two parallel transformer does not reduce the load by half on a single transformer, as the overall resistance ratios in the grid are changed. Therefore, also the current in $T10$ is slightly reduced. The reduction of the overall resistance in the grid and the different distribution of currents lead to a slightly higher current in transformer $T9_{\mathrm{HV}}$. However, with the objective function chosen in equation 1, a clear reduction of the GIC load on the grid is possible. Additionally, the high current of transformer $T7$ is effectively reduced with simply one additional neutral point connection.

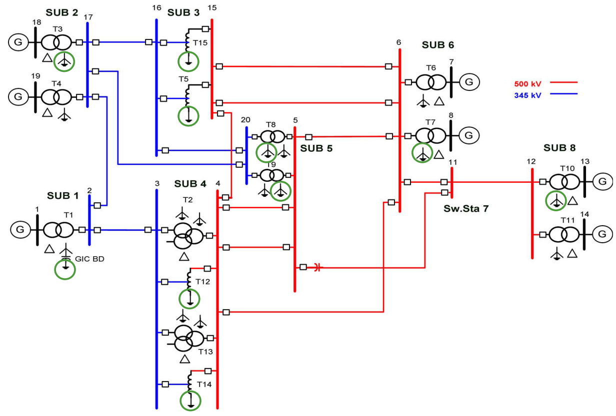

Fig. 1: Benchmark grid from [45]. Connected neutral points are marked green; all other neutral points are available for the mitigation algorithm.

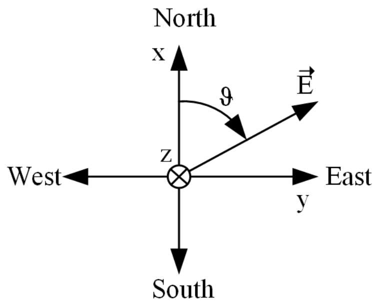

Fig. 2: Coordinate system as used in geosciences.

The additional connection of neutral points reduces the transformer zero-sequence for phase-to-ground faults and the short-circuit currents increase. Therefore, short-circuit calculations need to be performed and short circuit current ratings must be checked. A possible result of this short-circuit calculation may be, that the optimum neutral point change is not applicable. To overcome this problem, the optimization algorithm is performed several times and the resulting optimal neutral point change is forbidden in the next iteration. The results of the optimization cycle is depicted in Figure 4. The optimal solution would be the connection of $T6_{\mathrm{HV}}$, where the objective function is reduced to a value lower than 80% of the initial problem. However, if this led to inadmissible short circuit currents, another, less effective solution would be the connection of $T11_{\mathrm{HV}}$. The five alternative solutions in Figure 4 with the related objective function results show that at a certain point, alternative solutions lead to no satisfying result. In this case, this starts with alternative three, the connection of $T3_{\mathrm{HV}}$. The reason is that the

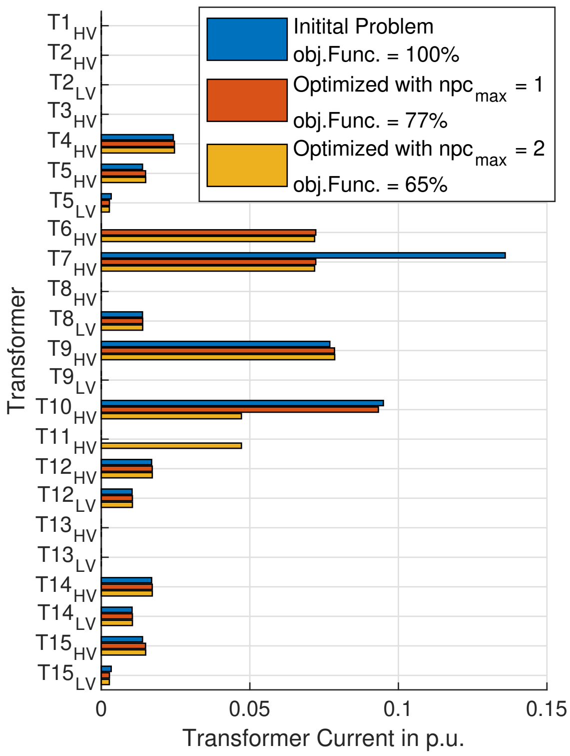

Fig. 3: Transformer currents of original and optimized neutral point configuration.

highest currents of $T7_{\mathrm{HV}}$, $T9_{\mathrm{HV}}$ and $T10_{\mathrm{HV}}$ can only be reduced effectively with a parallel connected neutral point and transformer.

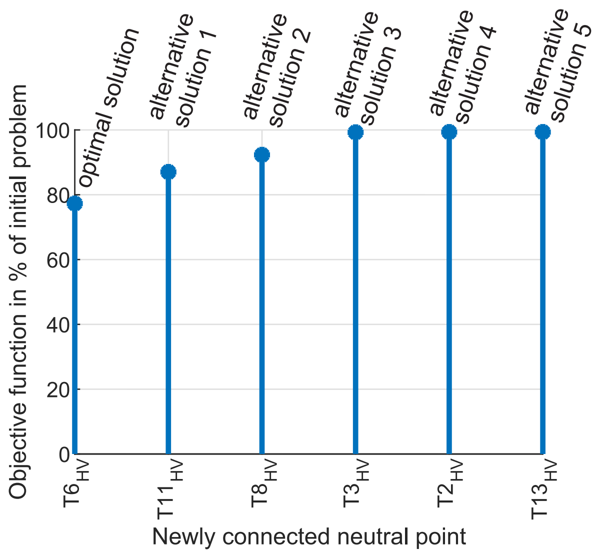

Fig. 4: Ranking of different optimization results.

In theory, it can be expected that the connection of all available neutral points may lead to the overall lowest objective function value, however, this would violate the given constraints. A similar satisfying result may also be possible with fewer neutral point changes. This would also mean less effort for grid operators while making the mitigation approach more applicable.
This is proven with the results in Figure 5. The increase of constraint (3) up to three allowed neutral point changes leads to a result close to the overall optimal solution and the highest currents in the grid are effectively reduced. Additional connections only lead to minor improvements but increase grid operators' operational expense.

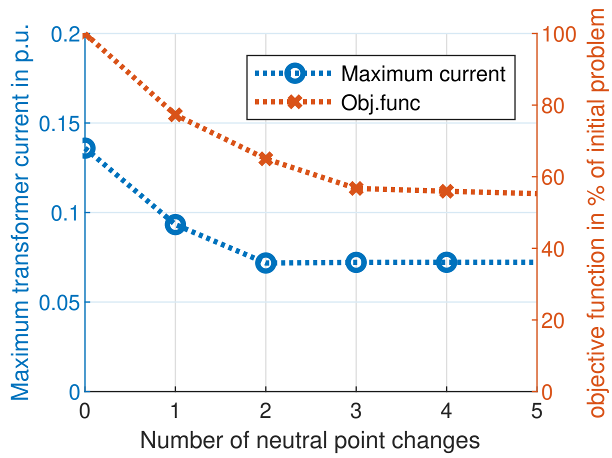

Fig. 5: Ranking of multiple neutral point changes.

It bears mentioning that the maximum transformer current as shown in Figure 5 occurs on different transformers for different numbers of neutral point changes: In the initial problem, it is at $T7_{\mathrm{HV}}$, with one additional connection it is at $T10_{\mathrm{HV}}$ and with two additional neutral points it is at $T9_{\mathrm{HV}}$. This is also depitecd in Figure 3.

3.3 Influence of E-field Direction

The direction of the induced electric field has a major influence on the neutral point changes. Solar storm forecasts predict the impact time, angle and magnitudes of the magnetic field changes, which lead to the induced electric field. With an electric field of $E_x = 1\ \mathrm{V/km}, E_y = 1\ \mathrm{V/km}$, the initial current in transformer $T7_{\mathrm{HV}}$ is the highest. For this case, the optimum for the objective function (1) is the connection of $T6_{\mathrm{HV}}$ and the reduction of current $T7_{\mathrm{HV}}$, as shown in Figures 3 and 4. A slight uncertainty in the space weather predictions immediately changes this result. To further investigate the influence of the electric field direction on the optimal neutral connections, the angle ϑ of the electric field with a magnitude of 1 V/km is changed. As shown in Figure 2, the angle is varied clockwise from 0° to 180° in increments of 1°. For each angle change, the optimization algorithm calculates the optimal neutral point change. With only one neutral point change, this leads to the reductions of the objective function as shown in Figure 6. Depending on the E-field direction, either the connection of $T8_{\mathrm{HV}}$, $T11_{\mathrm{HV}}$ or $T6_{\mathrm{HV}}$ leads to the highest reduction of the objective function. In case of a uniform electric field, as it is used in this study, the currents and effects repeat after 180°, as the transformer core would saturate in the other half-cycle. Therefore, the applied rotation from 0° to 180° covers all cases. Figure 6 shows that the mitigation effect is limited and very dependent on the electric field direction ϑ. The highest reduction with only one additional connected neutral point of 30% is possible, if the E field has a direction of 100°, which corresponds to a south-east and north-west direction. The maximum current in this case occurs in transformer $T7_{HV}$ and can be effectively reduced by connecting the parallel transformer neutral point of $T6_{HV}$.
The minimum reduction of 12% occurs in the range of 170°. In this field direction, the currents of several transformers are high but none has an extreme value. This means that even though the highest current is reduced to an applicable value, the currents of other transformers are still large and lead to high values in the objective function. To overcome this problem, more neutral point connections are needed.

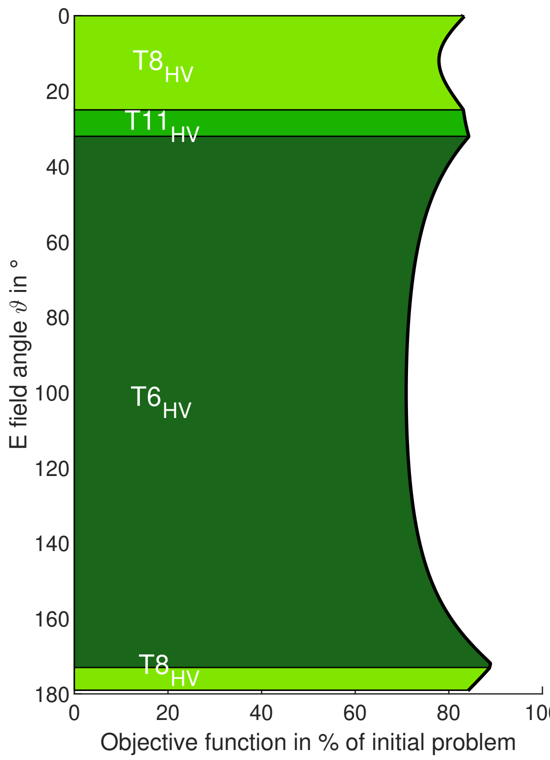

Fig. 6: Objective function depending on E-field direction and additional connected neutral points.

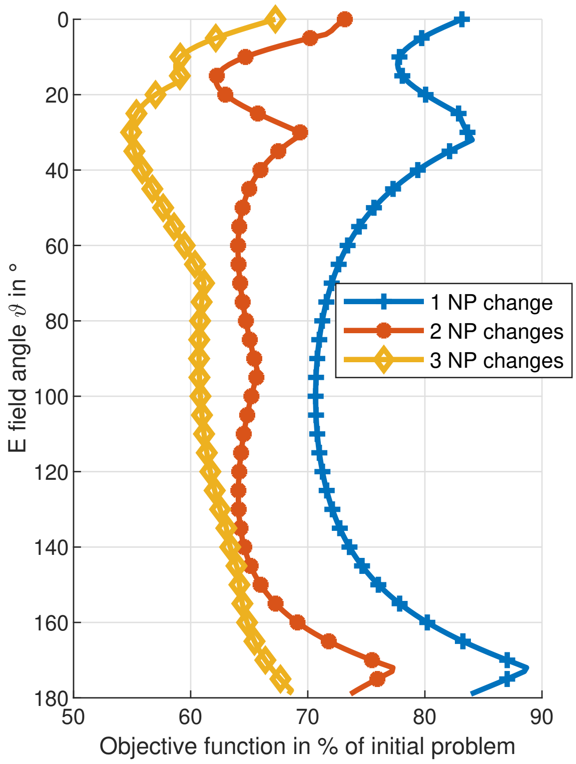

Fig. 7: Objective function depending on E-field direction for three different allowed neutral point changes.

Similar to what Section 3.2 conveys, more neutral point changes are allowed and the effect is analyzed in Figure 7. The three lines show the objective function in the percentage of the initial problem for one, two or three neutral point changes and the dependency on the E-field direction. As expected, and already presented in Figure 5, more neutral point changes lead to higher reductions of the objective function. The minimum, mean and maximum objective function in the percentage of the initial problem, as well as the maximum occurring current in p.u. for each of the three scenarios are shown in Table 1. The improvement rate is the highest between one and two additional neutral point connections, but of course three additional neutral points lead to the best results. A mean reduction of 39% is a remarkable result achieved without any additional assets.

The additional connected neutral points, depending on the E-field direction, are provided in Figure 8, which only includes the available neutral points. Depending on the allowed neutral point changes, either one, two or three, the additional connected transformers are marked in yellow.

Not every available transformer neutral point is utilized in the same way. Figure 9 shows the number of additional connections of the available transformer neutral points. This shows that some transformers are of higher importance for mitigation actions than others. Transformer neutral $T6_{\mathrm{HV}}$ is the one most used by this mitigation algorithm. This leads to the highest reductions during the E-field variations. on the contrary, transformers $T9$ and $T13$ are only used in a minor way, as the reduction achieved with them is small.

The high utilization rates of, e.g., $T6_{\mathrm{HV}}$ for this mitigation approach means that these transformers are of significant importance. A restriction of these transformers, as shown in Section 3.2 and in Figure 4 for only one E-field direction, leads to a significant drop in the mitigation effectiveness. A possible restriction reason in grid calculation software should be analyzed in detail, especially for transformers with a high utilization rates .

Table 1 Results depending on allowed neutral point changes

NP changes	max I in p.u.	min obj.Func. in %	mean obj.Func. in %	max obj.Func. in %
1	0.08	70	76	88
2	0.08	60	66	77
3	0.08	54	61	68

4 Conclusion

In this article, a new GIC mitigation method is presented and its effectiveness demonstrated. It is based on the fact that not all transformer neutral points in a grid are connected to the ground. An optimization problem is formulated that reduces the GIC impact on a system wide view and is implemented in the LFC simulation tool [10]. The optimization variable represents all neutral points in the grid and new connections are added to reduce the transformer currents by distributing it to other transformers. It is demonstrated that the algorithm can effectively reduce transformer currents. The effectiveness of this mitigation approach also depends on the direction of the electric field and the sensitivity of transformers in the respective direction. It is shown in a test grid that the formulated objective function can be reduced by up to 46% by connecting three additional transformer neutral points to the ground. Due to restrictions from the grid operation, the optimal connections may not be possible. Therefore, alternative solutions are also calculated and compared. The changes in grid topology can be easily tested for feasibility in other grid calculation software, e.g., to calculate the impact on fault currents. This modular approach has the advantage that information about power the plant operation of the whole grid is not needed in the LFC simulator.

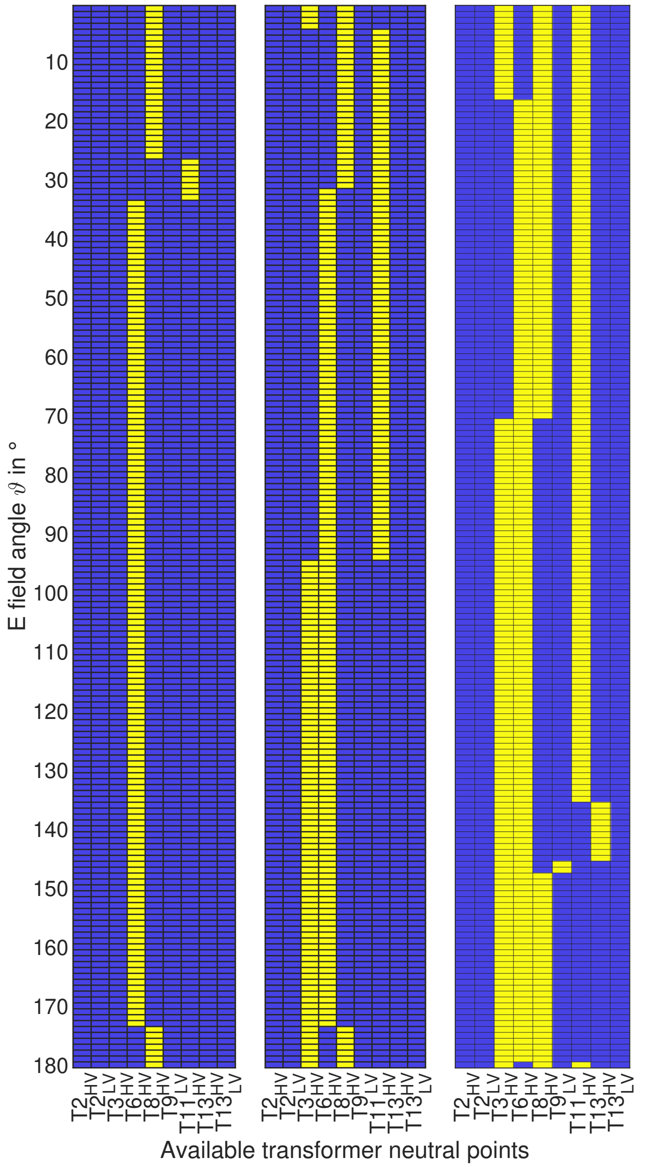

Fig. 8: Optimal additional neutral point connections for 1, 2 or 3 additional connections, depending on the electric field direction. Newly connected transformers are marked in yellow.

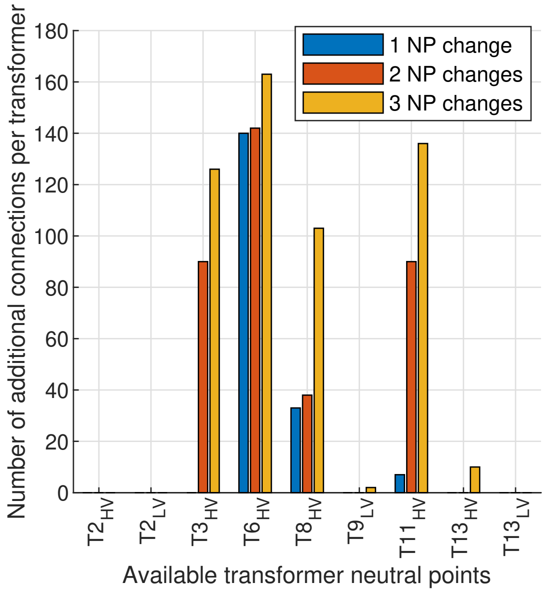

Fig. 9: Number of additional connections per transformer and scenario.

Other grid mitigation measures might still be required if the reduction of transformer currents through neutral point changes is insufficient or essential connections cannot be changed. However, the number of such measures can probably be decreased by using the suggested approach.

The objective function used herein aims for a distribution of high currents onto several transformers and therefore a reduction of the GIC load and possible damage to one transformer. The mitigation of additional reactive power demand of transformers or harmonic emissions due to saturation are dependent on the transformer type and therefore may result in different optimal neutral connections. Additionally, the constraints could be adapted to include more transformer details and limits. However, independent of the selected objective function, this mitigation approach reduces the GIC impact on the grid without any additional investments in new assets or mitigation devices and can be quickly applied to power grids.

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