Research on Optimal placement for GIC mitigation with Blocking Device

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Abstract. Geomagnetically induced current (GIC) caused by geomagnetic storms flows between the power grid and the earth would threaten the stable operation of the power system. Capacitor blocking device connected in series at transformer neutral point can directly block the DC path. However, due to the complexity of the DC path in the power system, before the installation of the blocking device, if global considerations are not taken into account, the adverse effects of GIC will not be reduced. Therefore, to study the position optimization of the capacitor blocking device is of great value. This optimization of placement of capacitor blocking device is proposed in this paper. Applying the idea of genetic algorithm, the installation quantity and installation position of the blocking device were calculated and compared with the traditional GIC non-optimal method, which verified the superiority of the genetic algorithm optimization solution.

1. Introduction

The geomagnetically induced current (GIC) caused by the geomagnetic storm flows between the power grid and the earth and poses a threat to the safe operation of the power system [1]. With the development of the national economy, power grid in China continues to develop toward high voltage, long distance and large capacity. These factors will increase the risk of damage to the power grid. At the same time, modern society has higher and higher requirements for power supply reliability. Therefore, the suppression of GIC in the power grid has attracted extensive attention [2][3][4].

The capacitor blocking device connected at the neutral point of the transformer can directly block the DC path. Therefore, installing capacitor blocking devices to reduce the adverse effects of DC bias on the power grid has commonly used in the power grid. However, due to the complexity of the DC path in the power system, when the DC blocking device is installed, without global consideration, it may not reduce the adverse effects of GIC and will also cause huge waste of resources.

Based on Xinjiang Planning Power Grid, this paper presents an optimization algorithm called multi-population genetic algorithm (MPGA) for the placement of capacitor blocking devices: under the premise that the effective GIC of all transformers in the system is less than the limit current, minimize the number of installations of blocking devices with the optimization of genetic algorithm. The numerical results indicate that by adopting the MPGA, noticeably less number of the capacitive blocking devices are required compared with the traditional placement.
2. GIC modeling
Due to the GICs of substations or transmission lines between different voltage levels may be mutually impact, the grid consisting of different voltage levels is considered in the modeling in this paper. The frequency component of GIC is mainly between 0.0001 Hz and 0.1 Hz. It can be regarded as a DC component compared with the grid frequency of 50 Hz, and it can only flow through the DC path which consists of transmission lines, substation transformers and the earth [4].

2.1. GIC calculation
Compared with single-voltage-level GIC calculations, multi-voltage-level GIC calculations differ only in transformer node and branch processing, and the calculation principle is basically the same [5].

Assuming that the geoelectric field $E$ caused by the geomagnetic storm is uniform and constant, the induced voltage of the line in the power grid can be superimposed from the induced voltage of the line in the north and east direction, that is [4]:

$$U = E_N L_N + E_E L_E$$  \(1\)

where $E_N$, $E_E$ are the magnitude of the induced geoelectric field in the north and east directions, and $L_N$ and $L_E$ are the effective distances of the transmission lines in the north and east directions, are given by

$$L_N = [111.133 \cdot 0.56 \cos(2\varphi)] \cdot \Delta Lat$$  \(2\)

$$L_E = [111.5056 \cdot 0.01872 \cos(2\varphi)] \cdot \cos(\varphi) \cdot \Delta Long$$  \(3\)

where $\Delta Lat$ and $\Delta Long$ are the latitude difference and longitude difference of the substation at both ends of the transmission line respectively, and $\varphi$ is the average of the latitude of the substation at both ends.

In order to make the final placement suitable for mitigating the adverse effects of the induced electric field in all possible directions on the power system, to calculate GIC for every possible angle in the range of $0°$-$360°$ is of great value [7]. Since the magnitude of the induced electric field can be linearly superimposed, the direction can also be orthogonal decomposed in both the east and the north directions. Therefore, after the value of the induced electric field Amplitude is given, the electric field is rotated in the range of $0°$-$360°$, suppose the angle between the direction of the induced electric field and the east direction is $\theta$, so that the $E_E$ and $E_N$ are given by

$$E_N = \text{Amplitude} \cdot \sin \theta$$  \(4\)

$$E_E = \text{Amplitude} \cdot \cos \theta$$  \(5\)

For any node $i$ in the grid, there is

$$J_i = u_i y_i + \sum_{k=1}^{N} u_i y_{ki} - \sum_{k=1}^{N} u_k y_{ki}$$  \(6\)

where $J_i$ is the sum of the branch current sources connected to the node $i$ which can be calculated by the induced electric field, $y_i$ is the grounding conductance of node $i$, $y_{ki}$ is the branch conductance between nodes $k$ and $i$; after calculating the node voltages $u_i$ and $u_k$, the GIC can be obtained. Its matrix form is

$$J = yv$$  \(7\)

2.2. Effective GIC
Since the autotransformer is generally used in China's UHV power grids, when the neutral point of the transformer is installed with a block device, the current flowing through the neutral point is zero,
however there is still existing bias current in the series winding \[8\][8]. Therefore, we use the effective bias current to evaluate the influence of the GIC on the transformer as defined by

\[
I_{\text{eff}} = I_H + I_L / k_t
\]

where \(k_t\) is the transformer turn ratio, and \(I_H\) and \(I_L\) are GICs flowing into the autotransformer winding through the series winding and the common series of the transformer.

The maximum of the maximum effective GIC and the average of the maximum effective GIC are used to evaluate the effect of the installing of blocking device on the grid are given by

\[
I_{\text{eff, max}} = \max \left\{ \max \{I_{ij}, j \in [0,2\pi]\} : i \in [1,N] \right\}
\]

\[
I_{\text{eff, ave}} = \frac{1}{N} \sum_{i=1}^{N} \max \left\{ I_{ij}, j \in [0,2\pi] \right\}, i \in [1,N]
\]

In (9) and (10), \(i\) is the substation number, \(j\) is the angle between the direction of the induced electric field and the east direction and \(N\) is the number of substations.

3. Optimization approach for capacitor blocking device placement

3.1. GIC equivalent model of Xinjiang planning power grid

In order to implement the global energy interconnection strategy, serve Xinjiang, and promote social stability and long-term stability in Xinjiang, Xinjiang State Grid Corporation plans to build a main grid of 750kV and above in Xinjiang. Xinjiang Planning Power Grid includes six 1000kV substations and thirty-seven 750kV substations, forty 750kV AC transmission lines, and five 1000kV AC transmission lines shown in Fig 1.

![Xinjiang Planning Power Grid](image)

**Figure 1.** Xinjiang Planning Power Grid geographical connection diagram

The GIC equivalent model of the Xinjiang planning grid is established by the GIC calculation modeling method described above. Each substation in the grid has two autotransformers running in parallel. The transformer winding branch is equivalent to the series winding resistance and the common winding resistance. The substation to the ground branch is equivalent to the grounding resistance, and the transmission line is equivalent to the series connection of the induced voltage source and DC resistance. Assuming that the GIC of each phase flowing through the line is equal, only the single-phase GIC will be considered in the calculation, the grounding resistance is 0.3Ω, and the line resistance is 0.01205Ω per unit length.

It can be seen from [10] that the DC current allowed by the transformer is related to the heating limit of the transformer winding and the iron core, the local overheating limitation of the transformer
structural parts, and the operational stability of the power system. When the DC current injected into the transformer $I_{dc} < 10$ A, the transformer works well and there is basically no obvious fault. However, when the $10 < I_{dc} < 50$ A, the temperature rise of the winding of the transformer increases, and the additional loss caused by the magnetic flux leakage increases rapidly, which cause the transformer to overheat and have hidden troubles. Therefore, we set 15A as the limit current for the transformer stable operation.

The single-phase GIC of each transformer of each substation node is calculated which is shown in Fig. 2. if the limit current for single-phase GIC of the transformer is 15A, the single-phase GIC of most substations of the grid under the influence of the electric field of 1V/km is larger than the limit current. Thus, to take effective measures to minimize the negative impacts of GIC on power system is of great necessity.

![Figure 2. The single-phase maximum GIC of each transformer of each substation.](image)

3.2. GIC suppression effect of traditional placement method

Installing the capacitor blocking device at the neutral point of the transformer can directly block the flow path of the GIC, but the installation of the blocking device will have a certain impact on the transformer in the neighbouring area, and this impact cannot be quantified. In addition, the cost of capacitor blocking device is high, it is unrealistic to install blocking device at the neutral point of all the transformers.

The traditional placement method is to install the blocking device according the GIC of each transformer, that is to say, calculate the maximum GIC of each transformer under the condition that the amplitude of the induced electric field is 1V/km, the magnitude of the induced electric field is in the range of $0^\circ$-$360^\circ$, and then sort the transformers by maximum GIC of each transformer in descending order, finally the capacitor blocking device is preferentially installed at the transformers with larger GIC, until the maximum effective GIC of all transformers of the grid satisfies the limit current.

It can be seen from the Fig 3 that when the placement is not considered to be optimized, the maximum effective GIC of the grid is not monotonously decreasing as the number of blocking device installations increases, even when the number of installations is 35, the maximum effective GIC of the grid is much larger than when the blocking devices are not installed. The maximum effective GIC of the grid is significantly decreased and satisfies the limit current until the number of installations of the blocking device reaches 40. As shown in Fig 4., the single-phase maximum effective GIC of each transformer of substation No.11 and No. 34 dose not monotonically diminish with the number of blocking device installations either, especially the GIC flowing through the transformer of No. 34 substation whose GIC was smaller before the installation of the blocking device will passively increase and even will be much larger than the limit current because of the installation on other transformers in the grid.
In summary, in the case of global considerations, installing blocking device on the substations with larger maximum effective GIC cannot reduce the impact of the geomagnetic storm on the power grid even if the GIC of the installed transformer can be reduced.

3.3. Algorithm principle for optimizing the blocking device placement

For the grids with a small number of substations, all the candidate solutions to the problem of the placement of the capacitor blocking devices can be enumerated by the exhaustive method. Calculate the maximum effective GIC of each solution, and find the optimal solution under the set limit current. However, as the number of substations in the grid increases, it will be much more difficult to solve the problem and may not even be solved.

It is a discrete problem whether or not the blocker is installed, and the multiple population genetic algorithm (MPGA) does not depend on the gradient in the optimization process. It has strong robustness and global search ability and is very suitable for solving such problems.

The MPGA begins to evolve from several sets of solutions (individuals) that represent solutions to the problem. Each individual in the population corresponds to a gene code to represent a solution to the optimization problem. For the optimization problem of the blocking device, an N-bit binary code is used to represent the solution to the problem. Each bit of the code has two encoding modes, 0 or 1, which indicates whether the corresponding substation is equipped with a blocking device or not. Each
individual is evaluated its superiority and inferiority according to the objective function and obtains its corresponding fitness value. Since the evolutionary principle of genetic algorithm is the process of increasing the fitness value, when construct the objective function, if the maximum effective GIC of the system satisfies the limit by adopting a solution placement, then the objective function of this solution is the number of “1” in its binary code, and its assigned fitness value is larger, while the fitness value is smaller of the one does not satisfy the limit. Individuals in the initial population compete for excellent individuals according to the fitness value, and generate new individuals after a series of genetic operations. The new individuals continue to evolve according to the same objective function, and assign fitness values. After several generations, the algorithm converges to one or several global optimal solutions.

3.4. Optimization result of the blocking device placement

The global optimal solution is obtained using the MPGA, with the following parameters: the transformer single-phase maximum effective GIC limit current is 15A, the amplitude of the induced electric field is 0.5V/km, chromosome length is 43, population number is 10, initial population size is 80, the crossover probability and mutation probability of each population are random numbers in [0.9, 0.95] and [0.01, 0.1], the retention algebra for the optimal individual is 20. Under the constraint that the maximum effective GIC of all transformers of the grid is less than 15A.

After running the MPGA optimization program for several times, the objective function can always converge to 29, which means the impact on the Xinjiang grid can be reduced to an acceptable level with only 29 blocking devices installed when the grid is affected by the magnitude of the induced electric field of 0.5V/km. The maximum effective GIC of all transformers of the grid is 14.8999A with the placement of the installation position: 1-3, 5-21, 23, 24, 27, 29, 37-39, 42 and 43 substation.

Under the same constraint that the maximum effective GIC of all transformers of the grid is less than 15A, the number of blocking devices of the MPGA optimal placement is much less compared with the traditional placement. The single-phase maximum effective GIC of all substations in the grid with the optimal placement obtained by MPGA is shown in Fig. 5, from which we can intuitively observe the inhibitory effect of GIC.

In order to further elucidate the superiority of MPGA in solving the problem of blocking devices under different conditions, the problem of blocking devices under the influence of different induced electric field in Xinjiang planning power grid was solved using MPGA. After running the optimization program, the optimization results and the GIC inhibition effect with the MPGA optimal placement shown in Table 1. can be obtained.

![GIC Inhibition Effect](image)

**Figure 5.** The single-phase maximum effective GIC of each substation with the MPGA optimal placement.
Table 1. The optimization results for different induced electric field

| Induced geoelectric field amplitude (V/km) | 0.5  | 0.75 | 1    |
|-------------------------------------------|------|------|------|
| Blocking device installation position     | 1-3, 5-21, 23, 24, 27 | 1-3, 5-21, 23-25, 27 | 1-3, 5-21, 23-29, 32 |
| Number of blocking devices                | 29   | 35   | 38   |
| $I_{eff, max}(A)$                         | 14.8999 | 14.7178 | 14.8343 |
| $I_{eff, ave}(A)$                         | 10.8112 | 11.9525 | 11.0065 |

Fig. 6 shows the number of blocking devices required for the grid under the influence of different induced geoelectric fields for two cases: 1) solve the problem using traditional placement method and 2) solve the problem using MPGA. In this figure, when the limit current is 15A, the number of blocking device of the MPGA optimal placement for different induced electric field is smaller compared with the traditional placement method.

![Figure 6](image)

**Figure 6.** Comparison of the number of blocking devices between the traditional placement method and the MPGA.

The above figures and tables show that MPGA has the irreplaceable superiority in solving the problem of the placement of the blocking device compared to the traditional placement method.

4. Conclusion

1) Installing the blocking device only at several substations with larger effective GIC can reduce the maximum effective GIC of the installed substations, however the maximum effective GIC of other substations can be passively increased and even exceed the limit current. Therefore, it is of great research significance to optimize the installation placement of the blocking device.

2) In the optimization calculation of the GIC blocking device placement for mitigating the effects of GIC of induced electric field magnitudes ranging from 0.5V/km-1V/km, in order to limit the maximum effective GIC of all transformers of the power grid to 15A or less, the number of blocking device of optimal placement obtained by MPGA is significantly smaller than the traditional placement method.

3) After adopting the optimized placement obtained by the MPGA optimization algorithm, the maximum and average values of the maximum effective GIC of the transformer are significantly reduced, which means that the adverse effects of GIC is effectively suppressed.

4) The future research plan for this paper includes multi-objective optimization calculation with more constraints, such as transformer reactive power loss caused by GIC, power flow constraints of grid operation, and finding more efficient algorithms to solve the problem.
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