Electrical Power and Energy Systems 103 (2018) 553–561

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

# Optimum damping resistance of potential transformers for mitigating ferro-resonance in gas insulated substations

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ARTICLE INFO

*Keywords:*
Ferro-resonance
Gas insulated substation (GIS)
Circuit breaker (CB)
Grading capacitance
Potential transformer (PT)
Damping resistance

ABSTRACT

Different methods are developed for mitigation of ferro-resonance in high-voltage gas insulated substations (GISs). The main components, which have impacts on probability of occurrence of ferro-resonance, are grading capacitance of circuit breakers (CBs) and internal loss of potential transformers (PTs). However, by using active or passive damping resistance in the secondary of PTs, the probability of occurrence of ferro-resonance can be decreased substantially. It is worth mentioning that the thermal limitations of PTs restrict us to dissipate a lot of energy in the damping resistance. Therefore, in this paper, both thermal and electrical aspects of ferro-resonance are considered and modeled to obtain the optimum value of damping resistance for mitigation of ferro-resonance. The proposed model to find the optimum value is based on robust optimization programming. The proposed model is tested and validated on two GISs in Iran.

## 1. Introduction

The over-voltage stresses in gas insulated substations (GISs) are categorized as stated in following.

- The first group is related to steady-state over-voltages in alternating current (AC) power frequency and its harmonics [1,2]. An overview of the state of the art in reactive power compensation technologies to compensate over-voltages and control voltage stability is proposed in [1]. The power frequency over-voltages in electrical grid of China are researched in [2], where they are categorized in three operating conditions, i.e., capacity effect of unloaded lines, unsymmetrical faults, and load shedding.
- The second group is transient over-voltages in scale of milli-seconds due to the load variation, switching, or earth faults [3–5]. The transient over-voltages created by switching the power factor correction capacitors are studied in [3]. The metal-oxide-varistor (MOV) surge arresters are evaluated in [4] to protect shunt-capacitor banks from over-voltages due to the lightning transients and switching. In [5], a controlled switching strategy is presented to reduce over-voltages due to transmission line closing and re-closing.
- The third group is fast transient over-voltages (FTOs) in scale of micro-seconds due to the lightening strikes on overhead lines, switching, and earth faults [6–8]. The transient over-voltage due to line-to-ground fault is studied in [6]. FTO waveform at various points of a commercial 550 kV GIS is simulated and measured in [7]. An over-voltage protection circuit is provided for protecting electrical equipment from transients on power lines in [8].
- The fourth group is very fast transient over-voltages (VFTOs) in scale of nano-seconds which occurs during the process of switching disconnect switches (DSs) and circuit breakers (CBs) [9–12]. A guideline is proposed in [9] to model and analyze VFTO phenomenon in GISs which is suitable for over-voltages in frequencies from 100 kHz up to 50 MHz. A 3-D model based on Maxwell numerical simulation is developed in [10] for analyzing VFTO associating with a 1100 kV GIS. The results of a full-Maxwell simulation performed on a real-life GIS geometry along with the modeling details are presented in [11] for better understanding of the VFT phenomenon and a significant reduction of product development time and prototyping costs. A feasible mitigation method for VFTO problem in an installed GIS is also proposed in [12].
- The last group is direct current (DC) over-voltages due to the trapped charges in some specific sections of GIS busbars [13–15]. The trapped charges left during DS opening are measured by using field tests in [13]. The influence of Sulfur hexafluoride (SF6) gas volume on charging of spacers of GISs under DC stress is studied in [14]. Mechanism and effect of DC charge accumulation on the surface of a solid spacer have been studied in [15].

Ferro-resonance phenomenon in GISs is a subset of first and second categories, as it is a steady state over-voltage and occurs following the switching of CBs [16]. It occurs due to the capacitive nature of busbars,

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https://doi.org/10.1016/j.ijepes.2018.06.031
Received 29 October 2017; Received in revised form 3 May 2018; Accepted 11 June 2018
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nonlinear inductance of potential transformers (PTs), and the grading capacitance of CBs [17]. It happens after opening of a CB of a feeder and before opening its DSs, i.e., before completely de-energizing the busbar and its respective PT. It is worth mentioning that the three basic elements, involving in ferro-resonance occurrence, have following impacts and characteristics in this incident.

- As busbars length is longer, their capacitive value is bigger and the probability of occurrence of ferro-resonance is strengthened. It is worth mentioning that the sensitivity of ferro-resonance occurrence probability to this element is very low.
- The second effective element is the PT of GIS busbars. It is required that this PT has high measurement accuracy standard, to adopt its output for controlling and protection purposes. To this end, it usually has narrower hysteresis loop and as a result, it has lower damping resistance value to mitigate ferro-resonance [18].
- The last element, which plays the major role, is the grading capacitance of GIS CB. It is used to balance voltage stresses on different sections of the CB during switching operation [19]. As the size of GIS CB is smaller, a larger capacitance should be used to protect against over-voltage stresses. Note that a larger grading capacitance for the CB increases the probability of occurrence of ferro-resonance.

The PT is thermally damaged by the ferro-resonance due to the heating. Ferro-resonance also affects on malfunction of protection equipments, and leads to the insulators failures [20]. These consequences are due to the over-voltages or over-currents. To mitigate and dissipate energy of ferro-resonance, four solutions can be implemented, which are presented in following.

- The first solution would be designing the size of busbars, grading capacitances, and PTs to reduce the probability of occurrence of ferro-resonance. Abdi et al. in [21] show that the bifurcation boundaries of ferro-resonance incident depend on the initial conditions and system parameters, i.e., grading capacitance and size of GIS busbars. The ferro-resonance initiation and its dependence on the remnant flux of PTs, are investigated in [22]. The impacts of initial conditions on the behavior of ferro-resonance circuit are also studied in [23]. Finally, an experimental and numerical investigation carried out in [24] on a circuit to determine to what extent the initiation of ferro-resonance depends on initial conditions and phase shift of the voltage source.
- Another solution would be interlocking the process of switching GIS CBs and DSs. Note that in some cases of switching, ferro-resonance may occurs with greater intensity and probability. In [25], avoidable switching operation or substation configurations are determined by using bifurcation diagrams.
- In the third solution, damping resistances are added in the secondary of PTs to mitigate and dissipate energy of ferro-resonance. The secondary of PT circuit is designed based on the PT core and its tolerable burden. Therefore, damping resistance would not be added in normal operation. It can be added in critical situation by using a magnetizing switch, as stated in [26]. Moreover, as shown in [27], damping resistance can be added in a broken delta configuration to only mitigate unbalanced currents. In [28], a proper damping resistance is chosen to minimize the probability of ferro-resonance occurrence in a 161 kV GIS.
- The last option would be using an active damping circuit to detect ferro-resonance occurrence. After detecting, a strong burden is added in a short period of time to mitigate ferro-resonance. In [29], a resistance is inserted in parallel to the secondary of PTs by using an activation signal, indicating that the ferro-resonance has occurred and it is liable to persist. Several verification tests for ferro-resonance detection techniques, e.g., artificial neural networks (ANN), are provided in [30]. In [31], a device is designed to synchronously insert resistance in parallel to the secondary of PTs and detach them in steps to avoid re-striking of ferro-resonance.

In previous literature, optimum value of damping resistance for mitigation of ferro-resonance, while respected PT are not damaged, was not determined. Note that decreasing damping resistance will be very likely to cause transformer over-heating, while decreasing damping resistance mitigates and dissipate the ferro-resonance energy. Here, a robust optimization model is proposed to optimize the value of damping resistance, considering both thermal and electrical aspects of ferro-resonance incident. The main contributions of this paper are stated in following.

- A comprehensive model is proposed, which considers both thermal and electrical aspects of ferro-resonance incident. As this circuit is nonlinear, it is analyzed by using harmonic balance method.
- The optimum value of damping resistance is determined to protect PTs and their elements against over-heating. Moreover, the chance of ferro-resonance occurrence is minimized at the optimum value of damping resistance. In this paper, this value is determined by using a robust optimization programming.
- Practical data loggings of Karoon 4 and Gotvand GISs in Iran are used to validate and verify the proposed model. Note that these two substations have different PT cores while they have a similar configuration.

The remainders of this paper are organized as follows.

In Section 2, the model is mathematically formulated. The safe and risk regions of ferro-resonance occurrence depend on system parameters, i.e., size of GIS busbars and grading capacitance, which are evaluated in Section 3. The optimum value of damping resistance for mitigation and dissipation of ferro-resonance energy is determined in Section 4. The proposed model is compared with the field tests in Karoon 4 and Gotvand GISs in Section 5. Finally, concluding remarks and future works are given in Section 6.

## 2. Proposed model for determining optimum damping resistance

The key components involving in ferro-resonance are shown in Fig. 1. As illustrated, a busbar and its respective PT is energized with a transmission line. After opening a CB, due to the existence of grading capacitance, a voltage is induced on its busbars and PT. Note that the circuit is similar with after closing DSs and before closing CB. However, as the closing speed of DSs is slow, the induced voltage during energizing GIS is not destructive.

In Fig. 1, equivalent capacitance of the busbar is denoted by $C_{busbar}$. This parameter depends on switching configuration of the substation.

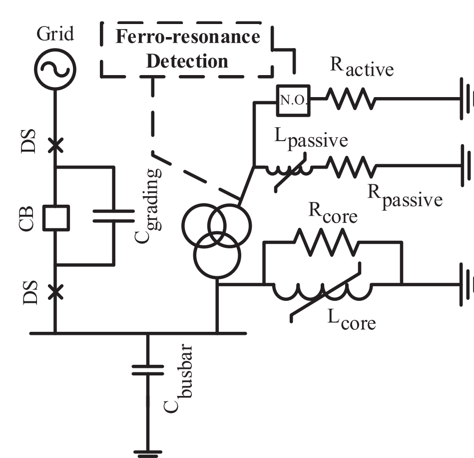


**Fig. 1.** Single line diagram of components involving in ferro-resonance.

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