International Journal of Research and Technology in Electrical Industry

journal homepage: ijrtei.sbu.ac.ir

Shahid Beheshti University

A Comprehensive Study Approach for Evaluation of Resonance and Ferro-resonance in HV Substations

Mohamad Ali Amini[1], Mehdi SalayNaderi[2,*], Ali Asghar Farokhi rad[3], Gevork B. Gharehpetian[2]

[1] Electrical Engineering Department, Iran University of Science and Technology, Tehran, Iran
[2] Electrical Engineering Department, Amirkabir University of Technology, Tehran, Iran
[3] Khuzestan Regional Electric Company (KREC), Khuzestan, Iran

ARTICLEINFO

Article history:
Received 20 November 2021
Received in revised form 07 March 2022
Accepted 04 April 2022

Keywords:
Resonance
Ferroresonance
HV Substation
Power quality
Transient analysis

Copyright: © 2023 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/)

ABSTRACT

Resonance and ferroresonance in power systems are categorized as two destructive phenomena especially in HV networks which their occurrence are being initiated in consequence of a power system event. Hence, the study of resonance and ferroresonance requires an exhaustive evaluation of possible network events in different network configurations. In each event, the analysis of network voltages is conducted based on identified allowable limits by IEEE 519 standard as evaluation critera. In this paper, a novel comprehensive study approach is used for resonance and ferroresonance phenomena study in a real power system (KzREC). The utilized approach comprises different steps including substation equipment modeling, EMT simulation of the probable switching events, evaluation of correspondence results, and finally detecting the probable ferroresonance occurrence. Furthermore, voltage and current limits are implemented to define impedance criteria for performing resonance evaluation of network buses. In this paper, the detailed evaluation results of a 230 kV substation (Andimeshk) are presented as an example substation. By performing the proposed evaluations, the probable condition which may lead to resonance and ferroresonance occurrence are identified. The results are highly valuable for network operators in the prevention of unintended overvoltages occurrencesubstation.

1. Introduction

The ferroresonance term has first introduced at a conference in 1921 [1], refers to the phenomenon of voltage fluctuations in electrical circuits, which must include at least the following elements:

- A nonlinear inductor (ferromagnetic and saturable)
- A capacitor
- A voltage source (usually sinusoidal)
- Low loss (low ohmic resistance)

Power grids are comprised of a large number of saturable inductive equipments (such as power

* Corresponding author
E-mail address: salaynaderi@aut.ac.ir
https://www.orcid.org/0000-0002-7021-6582
http://dx.doi.org/10.52547/ijrtei.1.1.57

transformers, inductive voltage transformers (VTs) and shunt reactors). In addition, the presence of capacitive equipments (such as cable capacitances, transmission line capacitances, capacitive voltage transformers, parallel or series capacitor banks, grading capacitors of circuit breaker) is the other factor that can cause the occurrence of ferroresonance in the network. The main feature of the ferroresonance is that when it occurs, more than one parameter of the network are changed simultaneously and non-linearly [2]. Transient instabilities, lightning overvoltages, energization or de-energization of power transformers or loads, faults or faults clearing, and etc. may initiate the ferroresonance occurrence. Consequently, the operating points of the system can suddenly jump from a steady-state point (power frequency sinusoidal) to an operating point which the magnitude of voltage and current harmonics can seriously damage the equipment. Although history of the ferroresonance phenomenon in the power grid is very long, there is limited information about this complex phenomenon and it cannot be analyzed or predicted by linear computational methods [3, 4]. The lack of information and inaccurate identification of the phenomenon's behavior causes damages and malfunction of some equipment. Hence, the evaluation of ferroresonance in power networks requires the detailed modeling of network equipment. Then, according to standard criteria, the occurrence of ferroresonance is being evaluated.

On the other hand, resonance is an electromagnetic phenomenon of energy exchange between capacitive and inductive equipments of the network which store electric and magnetic fields, respectively. Various power system equipments, such as transformers and transmission lines that are modeled with capacitive and inductive elements, may cause resonance in electrical systems. If resonant frequencies of the system are initiated under certain conditions, for example by voltage or harmonic currents, significant current amplification or overvoltages can occur [5]. The resonance frequency is being determined by series and parallel configuration of capacitive and inductive elements in resonance circuit. If the harmonic frequencies of the currents are close to the system's parallel resonant frequencies, the voltage magnification in the system will be very high, especially in critical resonance situations. This can lead to malfunctions or, in the worst case, damage to electrical system equipments [6].

The study of resonance and ferroresonance in transmission substations requires a comprehensive study approach for the detection of their probable occurrence. Hence, in this paper, a novel and comprehensive study approach is proposed for the determination of the probable occurrence of the resonance and ferroresonance phenomena in power networks. The proposed approach comprises modeling of substation equipment, simulation of the probable switching events, evaluation of correspondence results, and finally detection of probable resonance and ferroresonance occurrence.

In this paper, Khuzestan regional electric transmission substations are evaluated in terms of possible resonance and ferroresonance conditions. Wherein, in the following, second section reviews the basic concepts of resonance and ferroresonance phenomena. Then, third section defines the utilized methodology for evaluations of resonance and ferroresonance phenomena in transmission substations. Afterward, in fourth section, the evaluation results are defined.

2. Basic concepts

Resonance and ferroresonance are electromagnetic transients which their occurrence affect the power quality indices of the network. In this paper, evaluation of their occurrence in HV substations of Khuzestan regional electric network is performed to identify the possible condition which their occurrence are probable. Hence, in order to present the evaluation method, in this section, the basic concepts of these two phenomena are briefly reviewed.

2.1. Ferroresonance in the electrical circuit

To explain the ferroresonance concept, a simple circuit comprising the critical elements for the ferroresonance study is presented in Fig. 1.

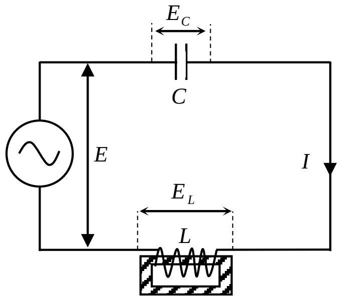


Fig. 1. Simple circuit for ferroresonance study

In an electrical circuit where an inductive element utilizes a ferromagnetic core, the relation between its voltage and current is non-linear. Fig. 2 shows the V-I characteristics of inductors and capacitors in the circuit.

As shown in Fig. 2, the inductor characteristic is non-linear and comprises linear and saturated regions. The non-linear characteristic shows that by increasing the inductor's voltage, the current would experience a large value. On the other hand, the V-I characteristic of a capacitor is linear. The equivalent impedance of series connection of non-linear inductor and linear capacitor results in a non-linear characteristic which is shown in the figure. By increasing the applied voltage from zero to a normal voltage (e), the operation point of M1 on the characteristic would determine the current value. In such conditions, the circuit current would be normal and the voltages across the elements would be lower than the applied voltage (e).

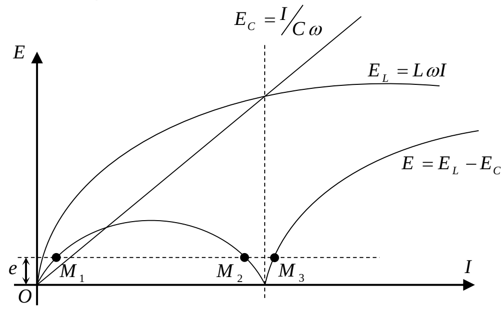


Fig. 2. V-I characteristics of inductor and capacitor in the circuit

As explained in the previous section, by the occurrence of an unwanted condition, such as network faults, it is possible for the operation point to transfer from M1 to M2 or M3. In M2 or M3, the inductor is working in the saturated region and therefore the circuit current is high. Therefore, the network elements experience an overvoltage. A detail explanation of ferroresonance and the effect of element's values are presented in [7].

2.2. Resonance in the electrical circuit

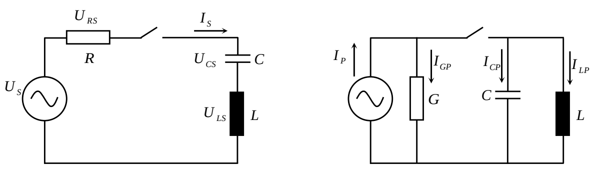
The phenomenon of resonance exists in a large diversity of physical systems and arises when the system is affected by periodical excitation with a frequency similar to its natural frequency of oscillation. When a system is excited, it tends to oscillate at its natural frequency. If the excitation source has the same frequency as the system's natural frequency, the system's response to that excitation can be very large. In order to have resonance in a system, it is necessary to have two forms of energy storage, with energy being periodically transformed from one form to the other, and vice versa: in mechanical systems these are kinetic and potential energy, in electrical systems, these are electrical and magnetic energy. Thus, electrical circuits with magnetic and electric fields have the capability of resonating. Electrical resonance occurs when the magnetic and electric energy requirements are equal, just as a mechanical system resonates when kinetic and potential energy requirements are balanced. The phenomenon of resonance has very useful applications in some fields. For instance, in telecommunications, resonant circuits are used to select a group of frequencies from a broader group. Such application, as an example, can be part of a radio filter that selects one station for reception, rejecting all others, utilizing a variable capacitor.

A useful application of resonance in electrical power systems is the design of filters for the suppression of harmful harmonics. However, the phenomenon of resonance can also be very destructive in power systems. Special caution is required in the design and operation of the power network to avoid the occurrence of resonance at the power frequency (50/60 Hz). Such resonance occurrence would lead to uncontrolled system overvoltages that could stress and damage equipment.

Electrical resonance occurs in a circuit when the capacitive reactance (X_C) equals the inductive reactance (X_L) at the driving frequency. This frequency, also called natural frequency, is given by (1).

$$f_n = \frac{1}{2\pi\sqrt{L \cdot C}} \tag{1}$$

There are two types of resonance: series and parallel. A basic scheme of series resonance is in Fig. 3 (a) and parallel in Fig. 3 (b).



a) Series b) Parallel

Fig. 3. Basic scheme of series and parallel resonance

For every combination of L and C, there is only one frequency (in both series and parallel circuits) that causes XL to exactly match XC; this frequency is known as the natural or resonant frequency (1). When the resonant frequency is fed to a series or parallel circuit, XL becomes equal to XC, and the circuit is said to be resonant at that frequency.

In the case of series resonance, all circuit elements are in one branch with a common current (Fig. 3 (a)). The circuit impedance is given by (2). At low frequencies, the reactance of the capacitor dominates and the phase angle approaches 90°, with current leading voltage. As the frequency increases, the inductive reactance becomes significant and, at the resonant frequency (1), it grows to the point of canceling the reactance of the capacitor. At the resonant frequency, the inductor and capacitor series combination becomes invisible and R is the total impedance of the circuit. Voltages ULS and UCS reach high amplitudes but have opposing phase angles and cancel each other out. Note that series resonance must be excited by an alternating voltage source. At series resonance, the circuit current is limited only by the resistor R up to a value IS = US/R. At frequencies above resonance, the inductor dominates the circuit characteristics and the phase angle approaches 90° lagging.

$$Z_{series} = R + j\left(\omega L - \frac{1}{\omega C}\right) \tag{2}$$

In the case of parallel resonance, all circuit elements are in parallel and they have the same voltage (Fig. 3 (b)). The circuit admittance is given by (3). At low frequencies, the susceptance of the inductor is large and dominates the circuit admittance. As the frequency is increased, the inductive susceptance diminishes and the capacitive susceptance grows until they become equal at the resonant frequency (1). This resonance frequency is the same for parallel and series circuits. Thus, series and parallel resonance occur at the same frequency for the same combination of inductor and capacitor. At the resonant frequency, the inductor and capacitor parallel combination becomes invisible and G is the total admittance of the circuit. Currents I_{CP} and I_{LP} reach high amplitudes but have opposing phase angles and cancel each other out. Note that parallel resonance must be excited by an alternating current source. At parallel resonance, the circuit voltage is limited only by the conductance G. As the frequency increases above resonance, the capacitive susceptance dominates the circuit characteristics. Thus, the circuit admittance reaches its minimum at resonance and becomes very large at low and high frequencies. In other words, at low and high frequencies, the parallel circuit impedance is very small but it reaches a maximum at the frequency of resonance. This behavior is the opposite of the series circuit, where the impedance reaches its minimum at resonance.

$$Y_{parallel} = G + j\left(\omega C - \frac{1}{\omega L}\right) \tag{3}$$

3. Proposed approach for evaluation of resonance and ferroresonance in HV substations

3.1. Ferroresonance Study in HV Substation

Generally, the ferroresonance in HV substations occurred as a consequence of faults or fault clearing, circuit breaker operation and etc. Therefore, in order to evaluate the probable occurrence of ferroresonance in each substation, first, the critical substation components are modeled based on [7]. Ferroresonance is a local phenomenon and, as a general rule, large network models are not necessary. Only the main elements directly involved in the Ferro-resonant circuit (i.e. non-linear reactance, capacitances and voltage source) need to be represented in detail. Therefore both in ferroresonance and resonance studies, the feeding network can be represented as a Thevenin source equivalent calculated at power frequency. The critical components of each substation in ferroresonance studies are overhead lines, power and voltage transformers, shunt reactors and capacitor banks [7]. In this paper, in order to evaluate the probable situation of ferroresonance occurrence, all possible switching operation in each HV substation is considered. The voltages of substation buses are evaluated based on IEEE 519 standard to determine the occurrence of ferroresonance. In IEEE 519 standard (which is reviewed in appendix A), the allowable voltage distortion is defined based on each voltage level, allowable individual harmonic and Total Harmonic Distortion (THD) as presented in Table .

Table I. Allowable individual harmonic and total harmonic distortion based on IEEE 519 standard

Bus Voltage at PCC	Individual Harmonic (%)	Total Harmonic Distortion THD (%)
$V \leq 1.0kV$	5.0	8.0
$1.0kV < V \leq 69kV$	3.0	5.0
$69kV < V \leq 161kV$	1.5	2.5
$161kV < V$	1.0	1.5

As shown in the above table, for each voltage level, the allowable voltage distortion is determined by IEEE 519 standard to evaluate the occurrence of ferroresonance. In addition, in each voltage level, the RMS value of bus voltage is compared to allowable bus voltage [8-10]. In this paper, voltage distortion of substation buses are evaluated in three time intervals (TIs): before CB operation, after CB operation and after CB reclosing. The schematic time diagram of defined intervals is shown in Fig. 4.

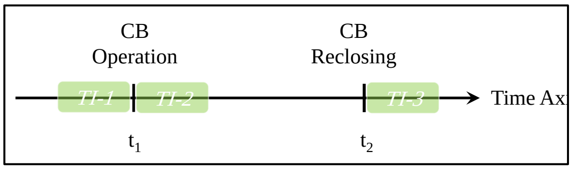


Fig. 4. Schematic time diagram of defined intervals

As shown in Fig. 4 three defined time intervals are evaluated in each CB operation. In addition, in each CB operation, three phases are evaluated to detect the probable occurrence of ferroresonance.

3.2. Resonance Study in HV Substation

The study of resonance in each HV substation is performed based on the proposed method in [8, 11]. In [8] a new method is proposed for the evaluation of impedance characteristic of network buses based on IEEE 519. According to IEEE 519, the allowable limit for current and voltages in each voltage level is defied. For further explanation, Fig. 5 shows the sample impedance characteristic in one of the network buses.

As shown in Fig. 5, the axis of harmonic order is divided into five zones based on the information provided in the standard in which the harmonic current limit is determined in each zone. By utilization of the allowable distortion of current and voltage, the acceptable value of impedance characteristic is determined as:

$$Z_{Zone_x}^{acceptable} = \frac{V^{h-allowed}\,(Table\ A.III)}{I^{h-allowed}\,(Table\ A.I - A.II)} \quad (4)$$

Where in zone x, according to table A.I-A.II of Appendix A, the acceptable impedance value ($Z_{Zone_x}^{acceptable}$) is calculated using the allowable voltage limit according to table A.III. The achieved impedance value is utilized for the evaluation of impedance characteristic of HV substation buses.

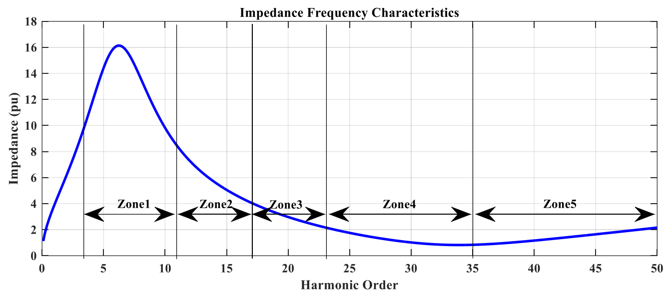


Fig. 5. Sample impedance characteristic in one of the network buses

3.3. Developed Infrastructure for Resonance and Ferroresonance Study

In order to provide an infrastructure for exhaustive study of resonance and ferroresonance evaluation, two well-known softwares are utilized: MATLAB and DIgSILENT Power Factory. DIgSILENT software is utilized in order to perform EMT studies of ferroresonance evaluation and impedance characteristic evaluation for resonance study. Then, the calculated results are transferred to the MATLAB software using a developed link to facilitate the evaluations studies with reference to the standard allowable limits. A schematic diagram of developed link is presented in Fig. 6.

Fig. 6. Developed Infrastructure for Resonance and Ferroresonance Study in Power Systems

As shown in the Fig. 6, two different softwares are utilized in this paper which constitute the study infrastructure for analysis of resonance and ferroresoancne in power systems. DIgSILENT software is implemented for performing power system related studies including EMT study for ferroresoancne analysis, load flow and short circuit studies for calculation of nominal and short circuit current magnitudes, and impedance frequency characteristic analysis for resonance evaluations. The calculation results are transferring to the MATLAB software for performing different analysis including FFT calculation, calculation of allowable voltage, current and impedance limits according to IEEE defined values, plotting comparative results and finally generating the final report.

4. Evaluation results

4.1. Current condition of the network

In order to evaluate the probable resonance and ferroresonance occurrence in each HV substation of the Khuzestan regional electricity network, the above-mentioned method is utilized. The Khuzestan regional electricity network comprises of 19 HV-400 kV and 37-230 kV substations. The defined evaluation process is performed on the HV substation one by one. In this paper, the detailed evaluation results of a 230 kV substation (Andimeshk) are presented. A single line diagram of the substation is shown in Fig. 7

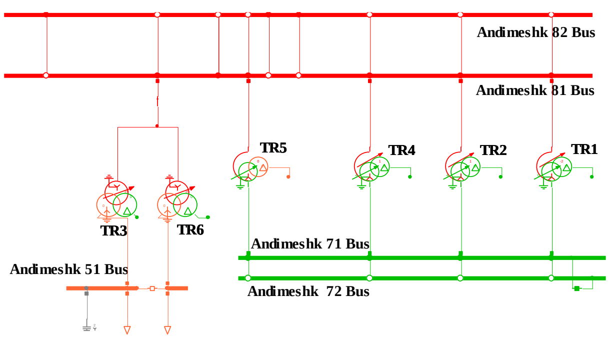


Fig. 7. Single line diagram of the Andimeshk 230 kV substation

As shown in Fig. 7, the substation contains three different voltage buses (230, 132 and 33 kV), 6 transformers and one capacitor bank. In order to perform an exhaustive study, all circuit breaker operations are considered and the resultant bus voltages are studied. Each circuit breaker is capable of single, two and three phase operations. Therefore, for each CB, seven operations are considered for three phases. In addition, in the ferroresonance study, for each CB, three time intervals are defined previously for evaluation. Therefore, for each CB, 3*7*3 different evaluation is performed for three parameters: Harmonic Distortion (HD), Total Harmonic Distortion (THD) and RMS value. For more explanation, the achieved results for one CB are presented here. Fig. 8 shows the maximum HD values in three phases for TI-1 in one circuit breaker (A7262 - Mentioned circuit breaker is one of 132 kV CBs - Andimeshk 71Bus.).

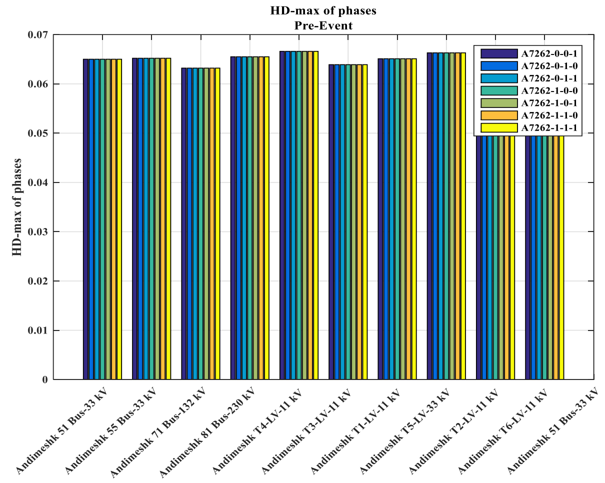


Fig. 8.: Maximum HD values in three phases for TI-1 in CB operation (A7262)

Fig. 8 shows the HD values in network buses for seven different operations of CB-A7262 in TI-1. As presented before in Table , the allowable limit for HD values in different voltage levels are satisfied. In addition, the THD values in TI-1 are presented in Fig. 9.

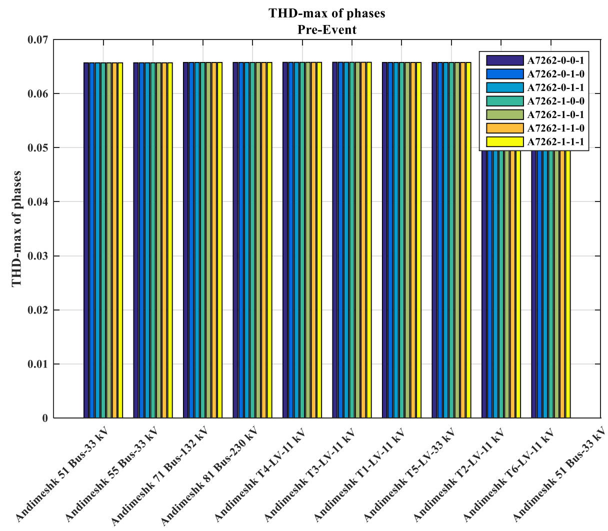


Fig. 9. Maximum THD values in three phases for TI-1 in CB operation (A7262)

Fig. 9 shows the THD values for different buses of Andimeshk 230 kV substation in TI-1. Comparing to Table , the THD values are within the allowable limit.

Fig. 10 shows the RMS values for different buses of Andimeshk 230 kV substation in TI-1.

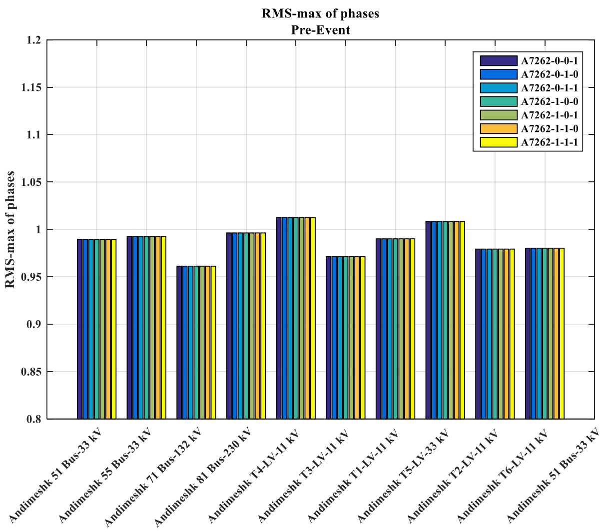


Fig. 10. Maximum RMS values in three phases for TI-1 in CB operation (A7262)

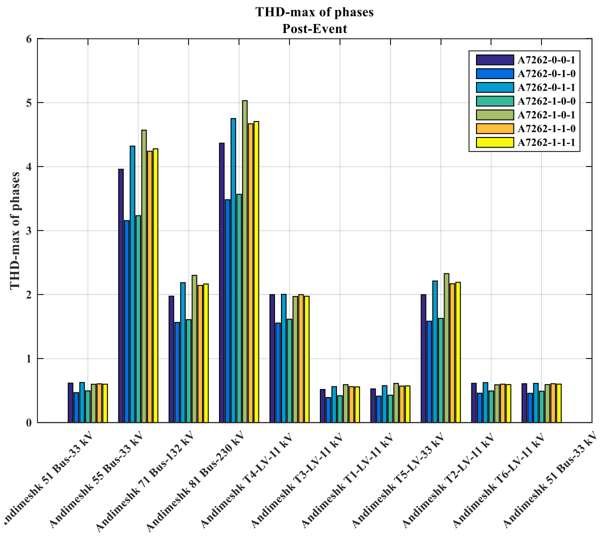


Fig 11. Maximum THD values in three phases for TI-2 in CB operation (A7262)

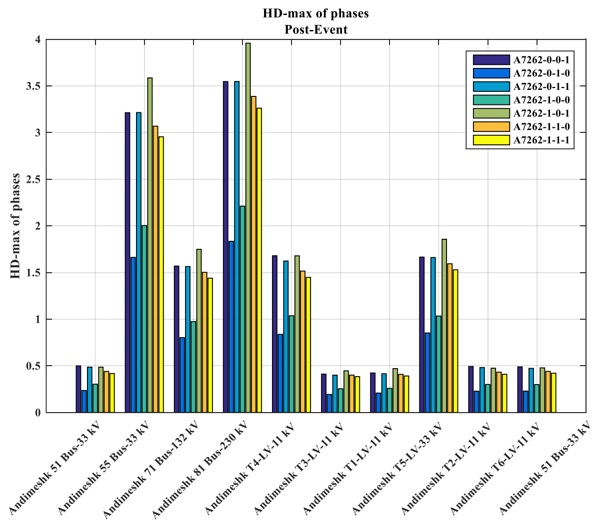


Fig. 12. Maximum HD values in three phases for TI-2 in CB operation (A7262)

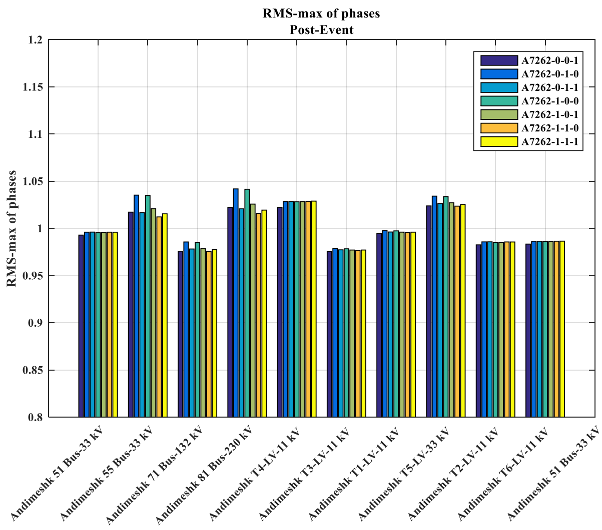


Fig. 13. Maximum RMS values in three phases for TI-2 in CB operation (A7262)

As shown in Fig. 10 the RMS values of bus voltages are in the allowable limit defined by IEEE standard.

In the following, Fig 11 to Fig. 13 shows the THD, HD and RMS values of bus voltages in TI-2 (i.e after CB operation).

As presented in the above figures, the THD and HD values in the 230 kV bus of the Andimeshk substation is out of the allowable limit. The resultant values indicate that the ferroresonance is occurs in some operations of A7262 CB and the 230 kV bus voltage is distorted. However, by consideration of the RMS value of the 230 kV bus in the mentioned CB operation, it is concluded that the ferroresonance severity is low and is neglectable since the resultant overvoltage in the 230 kV bus is not high enough to damage the equipment. The proposed approach is utilized in all HV substations of the Khuzestan regional electricity network.

On the other hand, the evaluation of the occurrence of resonance is performed by analysis of impedance characteristics of substation buses. The evaluation method is defined in the previous section. The impedance characteristics of bus 51 of Andimeshk substation in two operational conditions are shown in Fig. 14.

As shown in Fig. 14, the impedance characteristics of bus 51 while the capacitor bank is out of service are almost within the allowable limit. However, the impedance characteristic after the connection of the capacitor bank violates the allowable limit. This violation, increase the probability of resonance occurrence in harmonic order of 7-13. Flowing a harmonic current in the mentioned interval of harmonic order, would results in large harmonic voltage because of the occurrence of resonance. The mentioned evaluation is performed in all buses of network substations.

Fig. 14. Impedance characteristic of bus 33 kV of Andimeshk substation- with and without capacitor bank

4.2. Mitigation of Detected Resonance

In this section, the existing solutions to deal with the resonance phenomenon in the transmission network are categorized and presented. Strategies to deal with the resonance phenomenon are divided into active and inactive categories.

Passive solutions: refers to those methods of resonance mitigation which is performed in the design phase by modifying the power network, and therefore prevent the occurrence of resonance in the network.

Active solutions: refers to those methods of counteracting resonance that after identifying the phenomenon and subsequently, creating harmful overvoltages for the network and equipment, manual or automatic functions are activated and preventing from creating voltage or current stress on the equipment.

According to studies, in the 230 kV transmission substation of Andimeshk, if the 33 kV capacitive bank is connected to the 51 bus, there is a possibility of overvoltage due to resonance in the harmonic order of 10. It should be noted that due to the impedance characteristic of substation buses, power frequency resonance is not probable in this substation. Therefore, the possible occurrence of resonance at frequencies higher than the power frequency has been investigated. Since under normal conditions of the power network, there are no current flows in the network in harmonic orders other than the power frequency, so the occurrence of resonance overvoltage in these harmonic orders is not definite and is possible; Because only the presence of harmonic loads or saturation of magnetic cores in the network are the factors for the flow of harmonic currents in the network. Fig. 14 shows the impedance characteristic of bus 51 of this substation with and without capacitor bank. As shown in the figure, the value of the impedance characteristic of bus 51 in the condition of the capacitor bank in the harmonic order of about 10 is out of the allowable limit introduced by the standard. One of the effective ways to deal with overvoltages caused by the occurrence of resonance phenomenon is to modify the impedance characteristic so that in low harmonic orders where there is a possibility of harmonic currents, the impedance characteristic is a little less than the allowable limit.

For this purpose, a series reactor is integrated into the capacitive bank aimed at making a notch filter (single tune).

Fig. 15 shows the impedance characteristic of 33kV 51-bus of the substation.

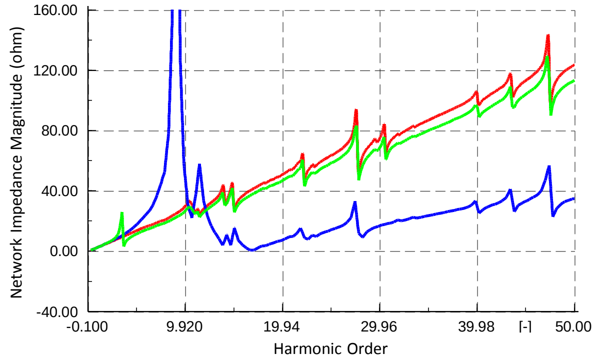


Fig. 15. Impedance characteristic of bus 33 kV of Andimeshk substation- Blue: With Capacitor bank, Red: Without Capacitor Bank, Green: With notch filter

As shown in the figure, the blue plot depicts the condition in which the capacitor bank is connected while the notch filter is not integrated. Besides, the red plot depicts the condition in which the capacitor bank is out of service and the red plot shows the impedance characteristic after the integration of the reactor to the capacitor bank. As it is concluded from the figure, the impedance characteristic is well improved and the resonance probability is resolved.

5. Conclusion

The occurrence of resonance and ferroresonance in power network result in overvoltages which are capable of damaging the network's equipment. In this research, efforts are made to identify the probable conditions for resonance and ferroresonance occurrence in Khuzestan regional electric network. Evaluation of ferroresonance is performed based on defined harmonic voltage distortion limits. IEEE 519 defines the harmonic distortion, total harmonic distortion and RMS values for different voltage levels in electrical networks. In addition, the defined allowable limits for current and voltage are utilized for defining an allowable limit for impedance characteristic in each voltage and current level. In general, the resonance and ferroresonance phenomena are initiated in consequence of network events such as intended or unintended CB operation. In order to perform an exhaustive research to identify the probable situation for the occurrence of resonance and ferroresonance, all CB operations including single phase, two phases and three phases in each substation are considered and evaluated. The resultant voltage waveforms in each substation's bus are evaluated in three time intervals including before CB operation, after CB operation and after CB reclosing. By performing the proposed evaluations, the probable condition which leads to the occurrence of resonance and ferroresonance are identified. The results are highly valuable for network operators for the prevention of unintended overvoltages.

6. References

[1] F. J. R. Margand, "Au sujet de l'existence de deux régimes en ferro-résonance," 1921.

[2] M. Yang, W. Sima, Q. Yang, J. Li, M. Zou, and Q. Duan, "Non-linear characteristic quantity extraction of ferroresonance overvoltage

time series," *IET Generation, Transmission & Distribution,* vol. 11, pp. 1427-1433, 2017.
[3] J. A. Corea-Araujo, F. González-Molina, J. A. Martínez, J. A. Barrado-Rodrigo, and L. J. I. T. o. P. D. Guasch-Pesquer, "Tools for characterization and assessment of ferroresonance using 3-D bifurcation diagrams," vol. 29, pp. 2543-2551, 2014.
[4] M. V. Escudero, I. Dudurych, and M. Redfem, "Understanding ferroresonance," in *39th International Universities Power Engineering Conference, 2004. UPEC 2004.*, 2004, pp. 1262-1266.
[5] C. Amornvipas and L. Hofmann, "Resonance analyses in transmission systems: Experience in Germany," in *IEEE PES General Meeting*, 2010, pp. 1-8.
[6] P. Mitra, A. De, A. J. I. J. o. E. P. Chakrabarti, and E. Systems, "Resonant behavior of EHV transformer windings under system originated oscillatory transient over voltages," vol. 33, pp. 1760-1766, 2011.
[7] Z. Emin, M. Martinez, M. Val Escudero, R. Adams, H. Bronzeado, B. Caillaut, *et al.*, "Resonance and Ferroresonance in Power Networks," *Electra - Cigrè,* vol. 272, pp. 81-85, 02/11 2014.
[8] M. Amini, A. Jalilian, and M. R. P. J. I. T. o. E. E. S. Behbahani, "A new method for evaluation of harmonic distortion in reconfiguration of distribution network," p. e12370, 2020.
[9] M. Amini, A. Jalilian, and M. R. P. J. E. P. S. R. Behbahani, "Fast network reconfiguration in harmonic polluted distribution network based on developed backward/forward sweep harmonic load flow," vol. 168, pp. 295-304, 2019.
[10] M. Amini and A. Jalilian, "Reduction of Short-Term Flicker Emission Using Genetic Algorithm-based Network Reconfiguration in Distribution Network," 2016.
[11] H. U. Patil, *Harmonic Resonance in Power Transmission Systems due to the Addition of Shunt Capacitors*: Arizona State University, 2015.
[12] T. M. Blooming and D. J. Carnovale, "Application of IEEE Std 519-1992 harmonic limits," in *Pulp and Paper Industry Technical Conference, 2006. Conference Record of Annual*, 2006, pp. 1-9.

7. Appendix a: defenition of IEEE std 519

The IEEE institute has introduced harmonic current and voltage limits to assess the harmonic status of power grids, including distribution and transmission networks[12]. The limits are defined based on Total Harmonic Distortion and Total Demand Distortion, according to (A.1) and (A.2), respectively.

$$THD_H = \frac{\sqrt{\sum_{i\geq 2} H_i^2}}{H_1} \qquad \text{1. (A.1)}$$

where H can be replaced by voltage and current.

$$TDD_I = \frac{\sqrt{\sum_{i\geq 2} I_i^2}}{I_{Max\,Demand}} \qquad \text{2. (A.2)}$$

IEEE Standard No. 519, which has been published to control harmonic distortions in power grids, determines the allowable harmonic distortion level at different harmonic orders according to Table A.I [12]. Table A.I represents the limits of harmonic voltages at a voltage level of 120 V to 69 kV and table A.II indicates the allowable range for a voltage level of 69 kV to 161 kV.

Table A.I. Current distortion limits for systems rated 120 V through 69 kV

I_{SC}/I_L	Maximum harmonic current distortion in presence of I_L — Individual harmonic order (odd harmonics)					
	3≤*h*<*11*	11≤*h*<*17*	17≤*h*<*23*	23≤*h*<*35*	35≤*h*<*50*	TDD
<20	4	2	1.5	6	3	5
20<50	7	3.5	2.5	1	0.5	8
50<100	10	4.5	4	1.5	0.7	12
100<1000	12	5.5	5	2	1	15
> 1000	15	7	6	2.5	1.4	20

Table A.II. Current distortion limits for systems rated above 69 kV through 161 kV

I_{SC}/I_L	Maximum harmonic current distortion in presence of I_L — Individual harmonic order (odd harmonics)					
	3≤*h*<*11*	11≤*h*<*17*	17≤*h*<*23*	23≤*h*<*35*	35≤*h*<*50*	TDD
<20	2	1	0.75	3	0.15	2.5
20<50	3.5	1.75	1.25	0.5	0.25	4
50<100	5	2.25	2	0.75	0.35	6
100<1000	6	2.75	2.5	1	0.5	7.5
> 1000	7.5	3.5	3	1.25	0.7	10

As shown in tables A.I and A.II, the allowable harmonic currents are divided into two general categories based on the voltage level. Also, at each voltage level, the harmonic current limits are also specified according to the short circuit level.

Furthermore, in this standard, according to the network voltage level, the THD limits and the individual harmonic distortion limit have been determined according to Table A.III.

Table A. III. Voltage Distortion Limit

Bus voltage V at PCC	**Individual Harmonic (%)**	**Total harmonic distortion THD (%)**
$V \leq 1kV$	5	8
$1kV < V \leq 69kV$	3	5
$69kV < V \leq 161kV$	1.5	2.5
$161kV < V$	1	1.5

3.