Elimination of ferroresonance in the distribution zone by high ohmic reactor-shunt limiter

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ABSTRACT

Electrical network components catastrophically fail as a result of aberrant system oscillations. Also, consequently leads to saturation in the ferromagnetic core elements. These factors induce distortions in the voltage and current waveforms as well as a large rise in voltage or current. This paper presents the role of distributed generation (DG) in contributing to ferroresonance investigation reduction in the distribution sector. A high ohmic reactor-shunt limiter (HOR-SL) is introduced as a novel technique based on a negative sequence component to mitigate ferroresonance. The proposed HOR-SL reduces the ferroresonance in distribution system (DS) by no more than 10.5 msec. A PSCAD/EMTDC software is used to model the ferroresonance phenomenon. The simulation results strongly show the effectiveness of using the proposed HOR-SL for limiting ferroresonant oscillations and creating stable orbit in the distribution sector. Case studies verified the effectiveness of the proposed technique in mitigating ferroresonance oscillations and keeping the security of the distribution zone.

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1. INTRODUCTION

The vast technical advancements of today make electrically connected devices more susceptible to system disruptions and transient phenomena, such as switching actions, the energizing and de-energizing of power system components, and faults [1]. The power system does not always work in a steady-state condition, but it may go via transient states. Despite the short time of transient cases compared to the steady-state conditions of the system, they cause serious problems to electrical systems [2]. There are two sorts of transitory problems: impulsive and oscillatory [3]. Ferroresonance is an oscillating phenomena that manifests itself in ferromagnetic electric circuits. Ferroresonance refers to voltage displacement or natural instability [4]. It can cause damage to system equipment, insulation and consumer's distribution devices. Also, it results in misoperation of protection devices due to overvoltage and/or overcurrent of peak value that can exceed more than twice of the normal value [5]. This phenomenon, caused by abnormal operations, results in thermal and electrical stresses [6]. Joseph Bethenod was the first to draw attention to this phenomenon in 1907. He suggested that nonlinear inductance was causing a resonance in the transformer, but Paul Boutherot first identified this phenomenon as ferroresonance in 1920 [7], [8]. The ferroresonance phenomenon is classified as low-frequency electromagnetic transients of frequency ranging from 0.1 Hz to 1 kHz [9]. Several unexplained failures can be attributed to these nonlinear phenomena [10]. The ferroresonance phenomenon in the electrical network has substantially increased recently. All parts of the electrical system from power transformers, components of the distribution system, and elements of the protection system are vulnerable to ferroresonance [11].

The occurrence of ferroresonance in potential transformer (PT) was discussed in [12] and recommendations to avoid the investigation of ferromagnetic resonance were provided. PT self-excitation characteristic was used to identify ferroresonance. Arroyo *et al.* [13] discussed the ferroresonance in PT and infer it through vibration analysis. Sridharan and Sugumaran in [14], a suppression circuit was suggested as a method to limit the harm effect of ferroresonance phenomena on a CVT. Pordanjani *et al.* [15] discussed the occurrence of ferroresonance in PTs during the system energization event. Solak and Rebizant in [16] discussed the faults in medium voltage (MV) network and its role in ferroresonance investigation at voltage transformer (VT). In addition, many studies have shown the occurrence of ferroresonance in PT in different parts of the network, and many solutions and inhibitor circuits have also been presented [17], [18]. Farm *et al.* [19] discussed the asymmetrical phases de-energization of the wind farm its role in ferroresonance activation.

Aref *et al.* [20] presented the prevalence of ferroresonance in the Montazer Qaem 63 kV substation. Polewaczyk *et al.* [21] explained the effect of power transformer energization in a 400 kV transmission grid on ferroresonance investigation. Rezaei [22] studied the effect of the transmission line outage on ferroresonance response in power transformer. Solak *et al.* [23] provided an analytical method to detect the ferroresonance phenomenon in (MV) Networks. In addition, there are many researches in the form of an analysis and a case study only, without presenting actual studies [24], [25]. Hajizadeh *et al.* [26] examined the effect of changing the type of distribution transformer on the ferroresonance response, but this study was conducted in a no-load condition. Thanomsat *et al.* [27] presented three ferroresonance cases in distribution system (DS) integrated with a PV system resulting from the break into interconnection between PV system and the transformer.

According to the previously discussed studies, ferroresonance is a common phenomenon in all areas of the power system, and a lot of research has been done on this topic. But the DS falls short of expectations in terms of its enthusiasm in researching this phenomena. Although the DS is the area most impacted by loads, any change in these loads has the potential to alter the network topology. This change could push the system into ferroresonance. The effects of the increased use of distributed generation (DG) in DSs and their effect in ferroresonance investigation have not gotten much attention.

Therefore, this paper focuses on studying the phenomenon of ferroresonance in DS and the effect of DG penetration on this phenomenon. It proposes a high ohmic reactor as shunt limiter (HOR-SL) based on the negative sequence detector as a ferroresonance mitigation method. The simulation was based on the PSCAD/EMTDC software.

The rest of the paper is organized as follow. Section 2 presents ferroresonance phenomena, its definition, the reasons for the occurrence of ferroresonance and ferroresonance problems. Section 3 presents simulation cases. Section 4 presents the proposed HOR-SL technique for mitigation ferroresonance and its control mechanism. The conclusion of the paper is given in section 5.

2. FERRORESONANCE MITIGATION

The term "ferroresonance" refers to a special case of resonance between the properties of an electrical network and a component that contains ferromagnetic material, such as a transformer or an inductor. The electrical network stability is threatened by the oscillatory phenomenon of ferroresonance. Ferroresonance results in significant, long-lasting overcurrent or/and overvoltage [28]. Ferroresonance is an unpredictable phenomenon that arises due to the interaction between equivalent system capacitance and non-linear [29]. Ferroresonance is a rare non-linear phenomenon in which energy fluctuates between a capacitive element and non-linear inductive element which alternatively becomes saturated. This phenomena causes the system to jump from a stable state to a stationary ferroresonant state. It results in many problems as shown in Figure 1. It is still disconcerting phenomena until today [30]. This phenomenon can occur with small changes in the parameters of the network so, it is difficult to be predicted. Investigating ferroresonance is a difficult endeavor, owing to the large number of factors that might influence the phenomenon's occurrence, as well as the phenomenon's great sensitivity to very minor changes in power grid parameters [31].

Ferroresonance differs from normal resonance, or as some researchers call it, linear resonance. Normal resonance is an expected phenomenon that results from an interaction between capacitance and inductance, unlike ferroresonance. Table 1 presents a comparison between ferroresonance and linear resonance [32]. There are many causes that lead to ferroresonance effect. The most important reasons are due to incorrect design, topology of network, the ferromagnetic core of transformer and unexplained causes. Table 2 explains these reasons, their percent and their description. The causes and problems of ferroresonance are summarized in Figure 1 [33].

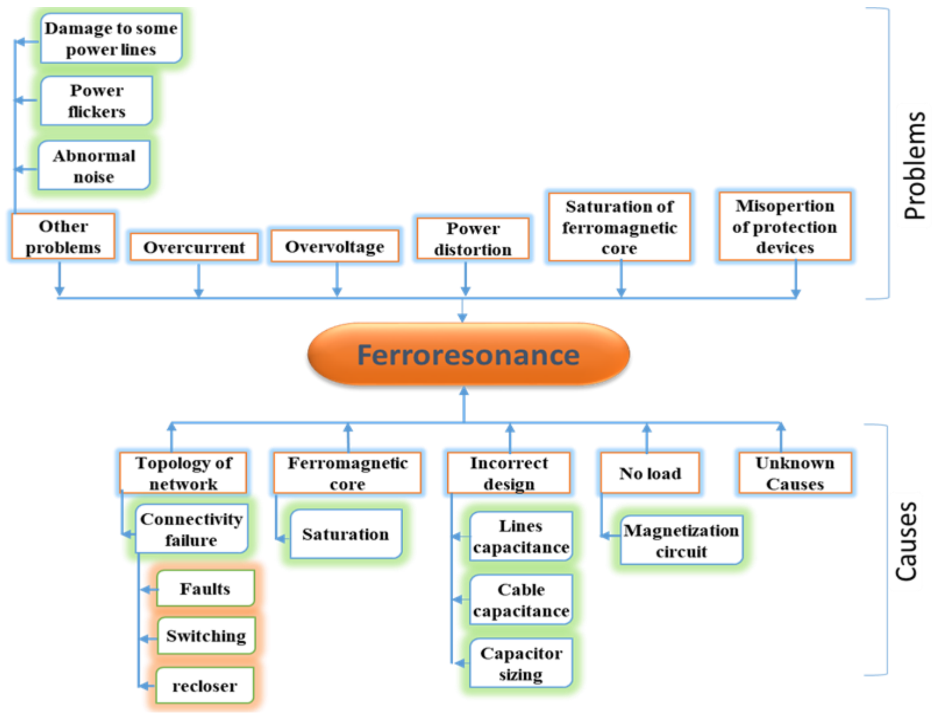


Figure 1. Ferroresonance causes and problems

Table 1. Comparison between ferroresonance and linear resonance

Types items	Ferroresonance	Resonance
Occurrence frequency	Ferroresonance occurs at many frequencies depending on the operating point of the magnetization curve.	Linear resonance occurs only at one frequency. So, it depends on the variation of the source frequency and system parameters
Difference	Ferroresonance occurs under saturation in the core of the nonlinear inductive element and interaction with system capacitance.	Linear resonance occurs from the interplay between capacitance and linear inductance.
Equivalent circuit	– Resistance – Capacitance Nonlinear inductance	– Resistance – Capacitance Linear inductance
Result wave	– Ferroresonance results in overvoltage and/or overcurrent with several wave shapes. It has many frequencies, depending on the response of the system.	–Resonance results in overvoltage and overcurrent but the wave keeps its sinusoidal shape and fundamental frequency.

Table 2. Main reasons lead to ferroresonance

Reason	Occurrence %	Description
Incorrect design	30	Ferroresonance phenomena can occur due to: – Incorrect design of any electrical network elements. – Incorrect sizing of capacitor bank. Incorrect determination of the length of cables and overhead lines.
Topology of network	15	Abnormal switching can cause ferroresonance investigations such as: – Connectivity failure after system faults have been cleared – Connectivity failure during the operating action Separation action, there was a disconnectivity failure.
Ferromagnetic core of transformer	20	Ferromagnetic nature of the core leads to the phenomenon of non-linearity to transformer inductance which lead to ferroresonance effect.
No load condition	25	The current in the primary side is mostly in the magnetic circuit due to the no-load condition, and this situation is conducive to ferroresonance.
Unexplained causes	10	Despite advances in research, ferroresonance remains a mysterious and unpredictable phenomenon in some cases. As a result, several DNs components were destroyed.

Therefore, the researchers focused on reducing the occurrence of this phenomenon to avoid its major technical and economic problems. Sima *et al.* [34] presented the using of resistor with two one-way controllable switches connected back to back implemented on the secondary side of the PT as a damping resistor to suppress ferroresonance. Price [35] presented the implementation of damping resistor connected with secondary winding of the transformer as suppress ferroresonance. Radmanesh and Fathi [36] relied on the use of a resistance with an electronic switches implemented on PT secondary side to reduce the ferroresonance, but presented a different control circuit for the switches. It presented the control of the conduction of this resistance by a mechanical switch or a saturable reactor, having a saturation voltage. The saturation voltage is higher than the rated secondary voltage of the transformer but still quite near to it. The saturable reactor is saturated when ferroresonance occurs and the resistance can damp ferroresonance. Also, Tseng and Cheng [37] used a parallel reactor with the secondary side of the PT for mitigating ferroresonance.

Matinyan *et al.* [38] introduced the use of thyristor driven spontaneous close shunt reactors as a solution to ferroresonance on a power transmission line which reduces the duration of the high voltage result from ferroresonance. A gas discharge lamp was used in [39] as a memristor emulator connected to the secondary of the Capacitive Voltage Transormer (CVT) to minimize the ferroresonance. Abbasi *et al.* [40] introduced ferroresonance limiter consists of damping resistor resulted in eliminate of chaotic ferroresonance oscillations started with series capacitors controlled by thyristor in the CVT. Izykowski *et al.* [41] introduced the design of two ferroresonance suppression circuit implemented on the step down side of the CVT. The first is to use a resistance only, and the second is to use RLC circuit. Chen and Yu in [42] recommended the implementation of damping resistor or air core reactor bank connected with transformer secondary winding as ferroresonance mitigation techniques. Akgün *et al.* [43] presented the design of converter acted as damping resistor emulators to mitigate ferroresonance oscillation. Heidary and Radmanesh in [44] presented smart ferroresonance limiter circuit that consist of four magnetically coupled windings. The primary winding and the PT are linked in parallel. The secondary winding is utilised to reduce ferroresonance overvoltage value.

3. FERRORESONANCE STUDY

In this section, two case studies are presented. The first is the investigation of ferroresonance in the DS in the proposed equivalent system. The investigation of ferroresonance in the DG case is covered in the second case study, along with how the DG affected the first case. It can be considered that the equivalent circuit of the power system is the distribution system feed from the overhead transmission line coming from the generation plant as shown in Figure 2. The study is implemented in a constant load of 12.5 kw.

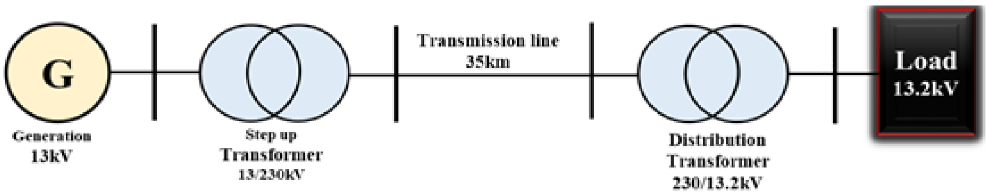
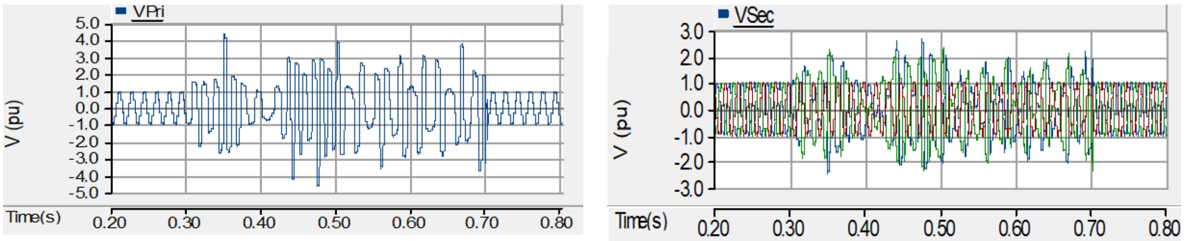


Figure 2. Single line diagram to the power system equivalent circuit

In the first case study, the system is operating as normal, however, if one sending end conductor of the transmission line are being disconnected as series fault, the voltage fluctuated with a high value on both sides of the transformer. The capacitance of the transmission line interacts with the inductance of the distribution transformer. It results in the chaotic ferroresonance mode on both sides of the transformer at the moment of one of the transmission line conductors is cut as shown in Figure 3. Figure 3(a) is obvious that, the value of the voltage rises more than 4 pu on the high voltage side and Figure 3(b) is obvious that, the value of the voltage rises more than 2.7 pu on the low voltage side.

In the second case, the DS is penetrated with a DG unit. The 16 kV DG unit is connected to the distribution zone through 16/13.2 kV, 30 MVA, transformer. The first type of DG was used, which providing the system with active power only. The described system is shown in Figure 4. With the penetration of DG in the system, the ferroresonance phenomenon is disappeared, even if one of the transmission line conductors or more are disconnected at any load value. In this case, the introduction of DG resulted in ferroresonance mitigation by altering the system topology. By studying all abnormal separation on DG and the transmission line, the ferroresonance was investigated only in the case of the separation of DG with the breakdown of phase A of the transmission line. Chaotic ferroresonance was investigated as shown in Figure 5. It is found that the voltage value was increased on the high voltage side for 4 pu as shown in Figure 5(a) and for 2.3 pu on the low voltage side as shown in Figure 5(b) and 2.8 pu on the DG side as shown in Figure 5(c).



(a) (b)

Figure 3. Ferroresonance in distribution system without DG, (a) Phase B of HV side and (b) Phases a and b of LV side

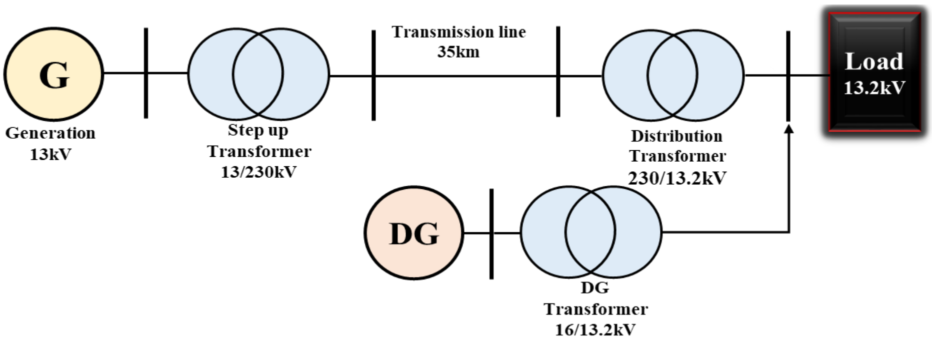
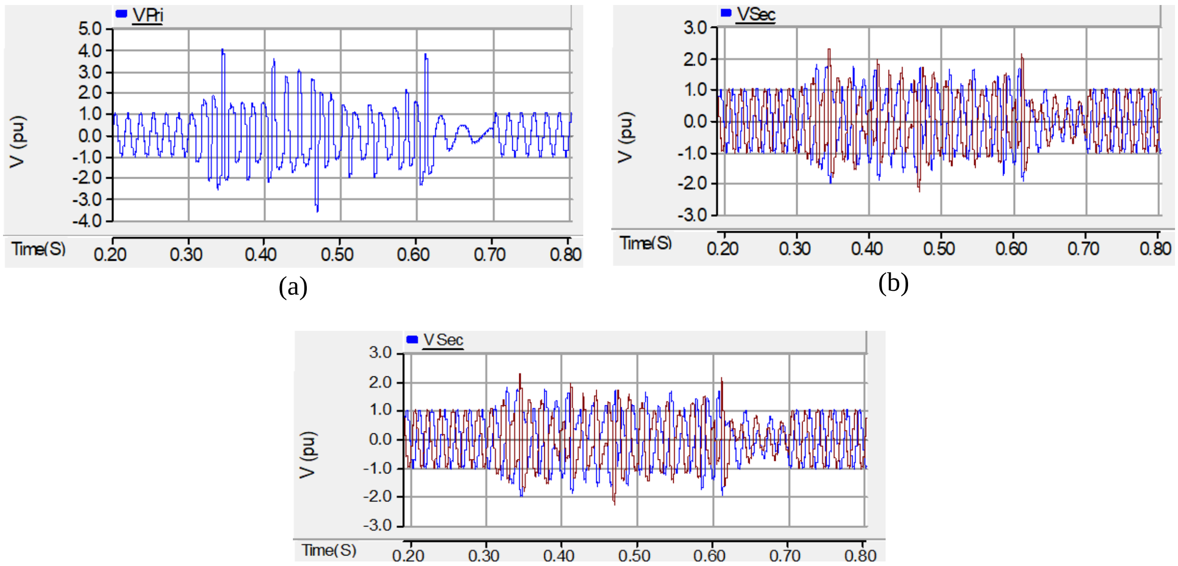


Figure 4. Single line diagram to the equivalent circuit of the power system integrated with DG



(a) (b)

(c)

Figure 5. Ferroresonance in the distribution system integrated with DG, (a) phase c of HV side, (b) phase b and c of LV side, and (c) phase B and C of DG side

All separation events are implemented at the instant 0.3 sec and the system recovers at the instant 0.7 sec. The study is conducted for a time of one sec. The voltage levels resulted from ferroresonance phenomenon are extremely high up to 4 pu. The abnormal switching action and the unexpected conductor failure may cause harmful damage to the power system parts. Therefore, it is important to provide system with protection against phase failure. Incorporating DG into the radial DS can reduce the incidence of ferroresonance, but may result in worse ferroresonance in some cases. So, the researchers must guide their efforts for optimizing the use of DG and avoiding ferroresonance.

4. MITIGATION OF FERRORESONANCE USING HOR-SL TECHNIQUE

A HOR-SL circuit and its control strategy is suggested as a ferroresonance mitigation technique. HOR-SL is regarded as device to be inserted in the network, in order to limit or clip ferroresonance. It composed up of a high ohmic reactor that was shunt-connected to the grid. The HOR-SL is modelled as a reactor (L) connected in series with a resistance (R). The procedures for obtaining deigned values are shown in Figure 6. The design process is initialized with acceptable range of (R and L), then the values are modified and updated until reaching the optimal values using a designed procedure which indicated by the flow chart of Figure 6. The HOR-SL is connected to the DS via a controllable switch which receives a control signal from a negative sequence detector element. The negative sequence is more than zero under the system's ferroresonance condition. The negative sequence component plays the role of detector only to connect the HOR-SL.

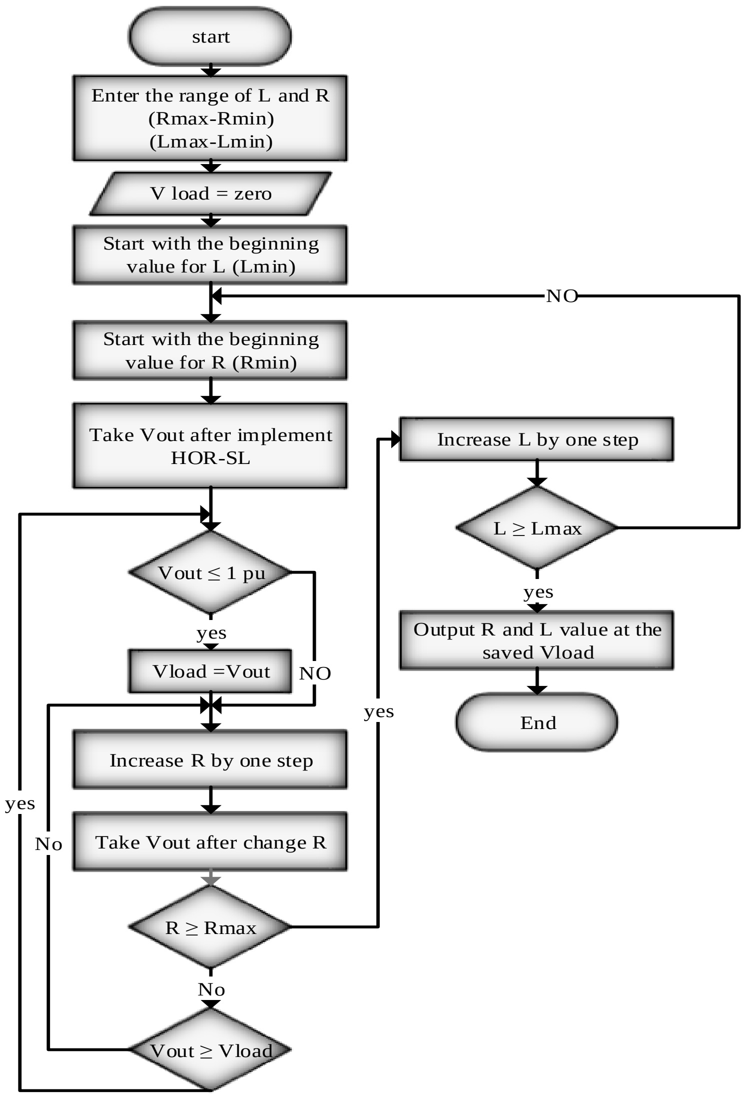


Figure 6. HOR-SL design steps

The control circuit is implemented to collect signals from the network and enter them on the negative sequence detector. The switch is signaled to shut when the negative component has a value, and the switch returns to its initial state of openness when the signal is stopped and the negative component no longer exist. When the system is powered on, the negative sequence has a small value. There form, the negative sequence was multiplied by a constant before entering the comparator to prevent shutting the switch at the system energized shown in Figure 7. The HOR-SL and the control circuit used to connect and disengage it to the grid are shown in Figure 7.

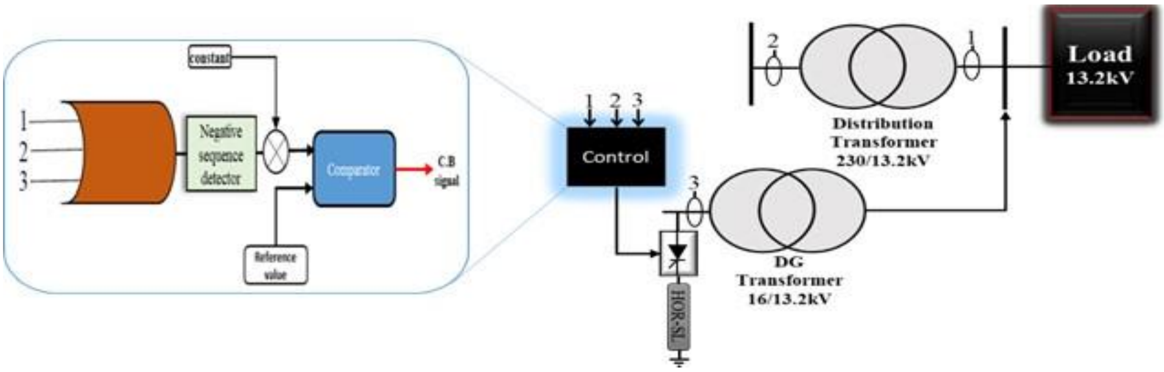


Figure 7. HOR-SL and its control circuit

The DS voltage in the first case while attaching the HOR-SL is indicated by a blue curve in Figure 8. After implementing the HOR-SL in DS in the first case, the ferroresonance was reduced from 4.2 pu to 0.6 pu in the transformer primary side as shown in Figure 8(a) and from 2.8 pu to 0.6 pu in the transformer secondary side as shown in Figure 8(b) and Figure 8(c). HOR-SL values are 0.01 H and 1 kΩ. The negative sequence component in the first case is shown in Figure 9. The separation and recovery points, as well as the connection and disconnection of the HOR-SL in the grid, are depicted in the figure. Figure 9 lower half displays the controlled switch's trip signal. It is evident that the difference between the abnormal separation time and the HOR-SL connection time is 9.9 msec. The difference between the recovery time and the HOR-SL disconnection time is17.8 msec.

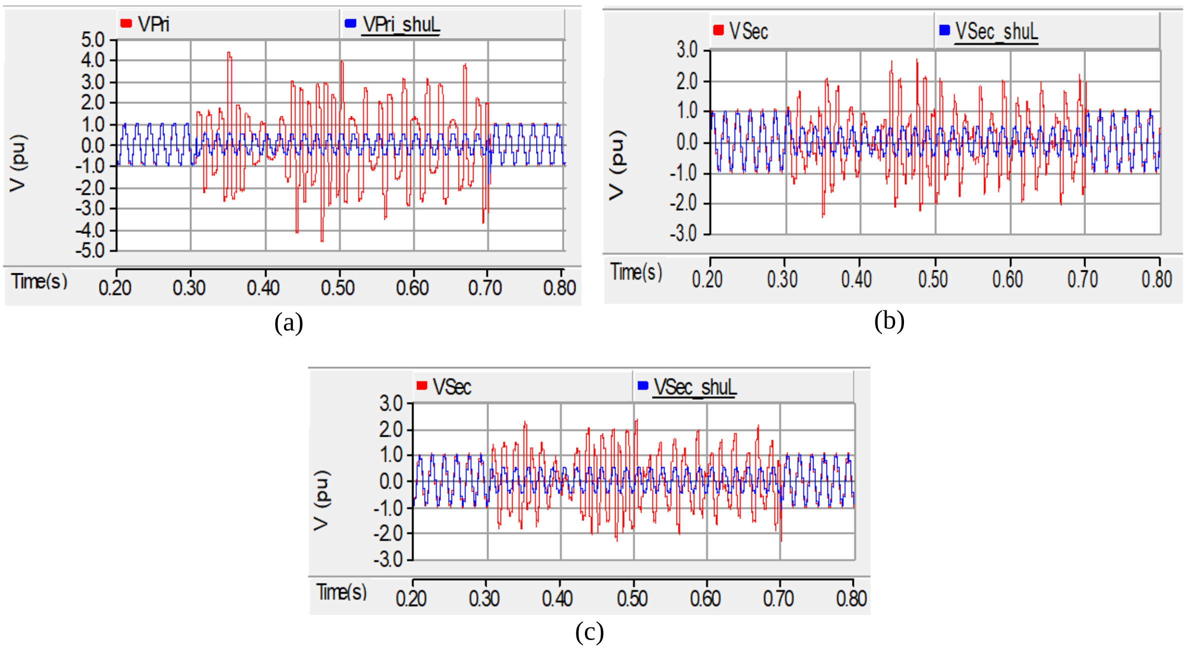


Figure 8. Voltage waveform with and without implementation of HOR-SL in DS, (a) phase B of HV side, (b) phase a of LV side, and (C) phase b of LV side

The DS voltage in the second case while attaching the HOR-SL is shown as a blue curve in Figure 10. It is concluded that the proposed HOR-SL is able to suppress ferroresonance before it reaches a high value that endangered the components of the electrical system. After implementing the HOR-SL in DS penetrated with a DG unit in the second case, the ferroresonance was reduced from 4 pu to 1 pu in the transformer primary side as shown in Figure 10(a), from 2.3 pu to 1 pu in the transformer secondary side as shown in Figure 10(b) and Figure 10(c), and from 2.8 pu to 0 pu in the DG side as shown in Figure 10(d) and Figure 10(e).

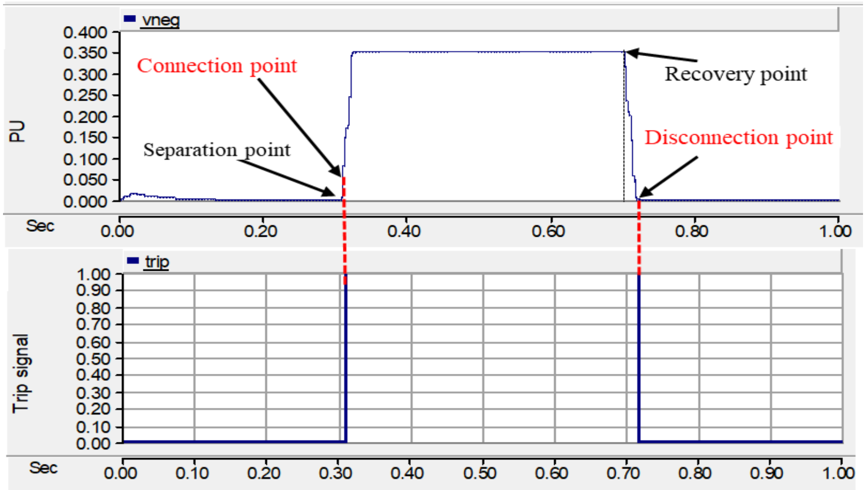


Figure 9. Negative sequence component and trip signal of the switch at the first case

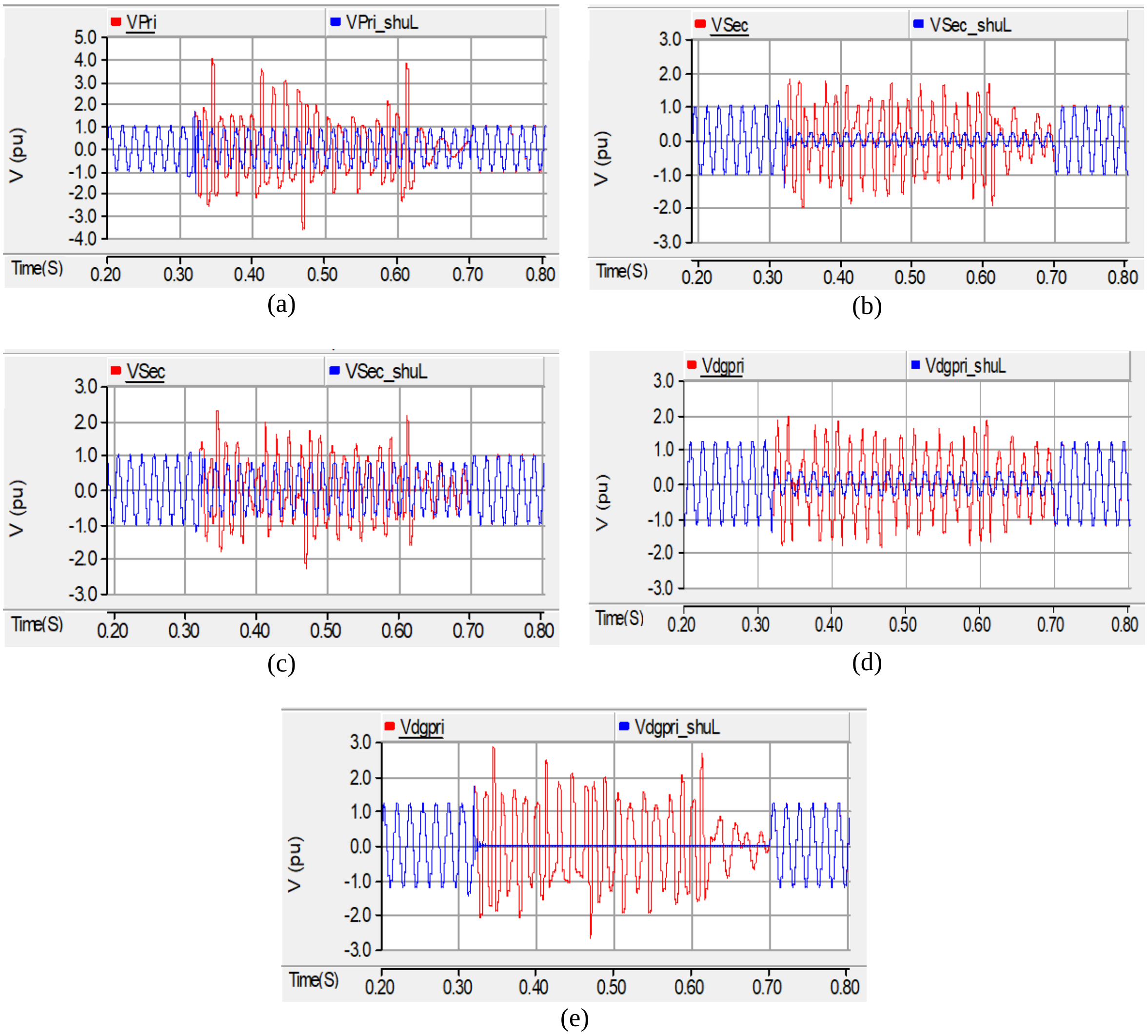


Figure 10. Voltage waveform with and without implementation of HOR-SL in DS integrated with DG, (a) phase c of HV side, (b) phase b of LV side, (c) phase c of LV side, (d) phase B of DG side, and (e) phase C of DG side

HOR-SL values are 0.01 H and 820 Ω. The negative sequence component in the second case is shown in Figure 11. The separation and recovery points, as well as the connection and disconnection of the HOR-SL in the grid, are depicted in the figure. Figure 11 lower half displays the controlled switch's trip signal. It is evident that the difference between the abnormal separation time and the HOR-SL connection time is 10.4 msec. The difference between the recovery time and the HOR-SL disconnection time is 15.5 msec. It is concluded that the proposed HOR-SL is able to suppress ferroresonance before it reaches a high value that endangered the components of the electrical system.

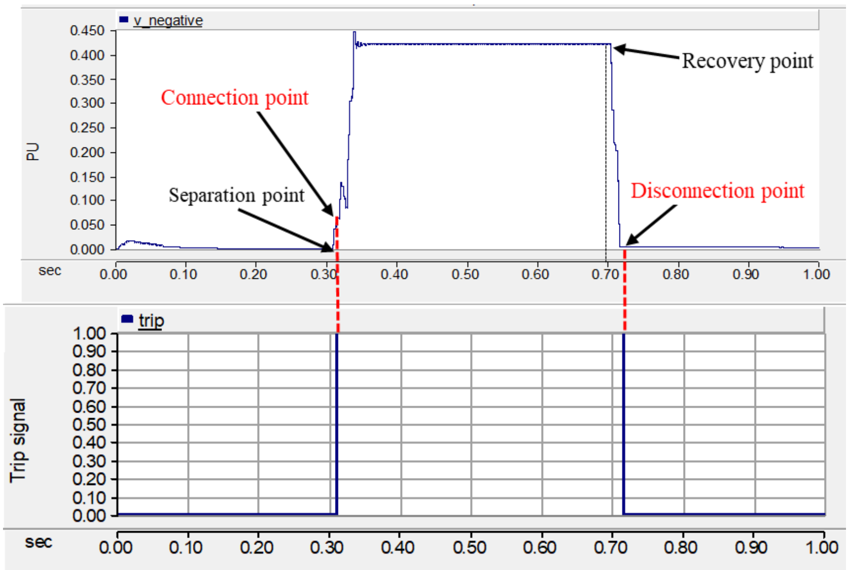


Figure 11. Negative sequence component and trip signal of the switch at the second case

5. CONCLUSION

This article discussed the occurrence of ferroresonance in the DS. A new method (HOR-SL) of eliminating ferroresonance oscillations in in the distribution system has been proposed. Results showed that the penetration of DGs into the distribution zone has an active role in mitigating the investigation of ferroresonance. The ferroresonance is appeared only during disconnecting the DG and a phase of the transmission line with keeping the DG transformer connected to the distribution side. Case studies verified that the rate of ferroresonance occurrence in the case of DG integration is lower than that occurs in the case of DG unintegrated distribution system due to the need for separating more than one position at the same time. The proposed HOR-SL is able to mitigate the state of ferroresonance in DS within a time of no more than 10.5 msec. The proposed control circuit has an active role to pick up the ferroresonance before it crossed the rated voltage. It was able to connect the HOR-SL at the instant 0.3104 sec before the voltage exceeded 1pu. Thus, the ferroresonance mitigation using this technique is efficient and fast. This study is useful in mitigating ferroresonance oscillations created in the distribution system.

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