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RESEARCH ARTICLE

High Ohmic Reactor as a Shunt Limiter (HOR-SL) Method for Ferroresonance Elimination in the Distribution System

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ABSTRACT Aberrant system oscillations cause electrical network components to malfunction in a catastrophic way. Additionally, this results in saturation of the ferromagnetic core components. These variables cause a significant increase in voltage and/or current, as well as aberrations in the waveforms of voltage and current. The contribution of Distributed Generation (DG), to the decrease in ferroresonance investigation in the distribution zone, is discussed in this paper. A new method to reduce ferroresonance using the High Ohmic Reactor (HOR) as a Shunt Limiter (SL) is presented. It is based on the measurements of the negative-sequence components. The proposed HOR-SL reduced the ferroresonance occurrence in the Distribution System (DS) by a time value of no more than 23 milliseconds. The proposed HOR-SL method is compared with the Series Resistance (SR) and Series Tuned LC Limiter (STLCL) methods. The results obtained using the proposed HOR-SL are better than the ones obtained using SE and STLCL. In terms of the voltage and the time taken to mitigate the ferroresonance. The ferroresonance phenomenon is modelled with the help of the PSCAD/EMTDC software. The results obtained demonstrated the effectiveness of implementing the suggested HOR-SL for suppressing ferroresonant oscillations to restore the original state of stability of the distribution network. Case studies strongly proved the effectiveness and robustness of the proposed method in reducing ferroresonance oscillations and maintaining the security of the electrical components in the distribution network.

INDEX TERMS Ferroresonance, distributed generation (DG), distribution system (DS), PSCAD/EMTDC, high ohmic reactor (HOR) as a shunt limiter (HOR-SL).

I. INTRODUCTION

Electrically connected components and devices are more vulnerable to transient-state phenomena and system disruptions due to the great technological breakthroughs of today. These phenomena include the system faults, switching operations, and the energizing or/and de-energizing of electical power system components. The electric power system networks may experience transient states rather than operating in a steady-state mode. Athough transient situations last only a brief in comparison with the steady-state circumstances of the system, they seriously damage electrical systems [1], [2]. There are two different categories of transitory problems oscillatory and impulsive [3]. Ferroresonance is an oscillating-bevaviour phenomenon that appears in electric networks. It is a term for abnormal instability or voltage displacement [4]. Insulation, consumer distribution devices, and system hardware may all be damaged. In addition, it causes protective systems to malfunction due to peak overcurrent or/and overvoltage values that can be more than twice of the average value [5]. This problem, caused via abnormal operation or switching, results in electric and thermal stresse effects [6]. The first person to call attention to this phenomenon was Joseph Bethenod in 1907. He proposed that resonance in the transformer was caused by nonlinear inductance, but Paul, B. first named it as ferroresonance in 1920 [7]. The ferroresonance phenomena is

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categorized as electromagnetic transients of low frequencies between 0.1 Hz and 1 kHz [8], [9]. These nonlinear occurrences have been linked to some mysterious failures [10].

In the electric networks, the ferroresonance phenomena has increased significantly recently. Ferroresonance can affect any component of the electrical system, including power transformers and the components of the protection and distribution systems [11].

Behdani et al. in [12] introduced the investigation of the ferroresonance phenomenon caused by quasi-DC type Geo-magnetically Induced Currents (GICs) in the power transformer used with series capacitor-type compensated networks. A mathematical analysis was carried out to demonstrate the effect of GIC on ferroresonance. For verification, an experimental test setup was introduced. Under the ferroresonance occurrence caused by GICs, the authors implemented a case study using an EMTP-RV environment to evaluate the impacts of various concerning parameters to the system such as the level of system compensation, the loading of the system, and the grounding resistance of the substation. The results showed that GICs can greatly enhance the vulnerability of power transformer to the event of ferroresonance phenomena in case of series capacitor-type compensation power grids. Akinci et al. in [13] modelled the 380 kV electric power grid of turkey via numerical simulations implementing MATLAB software. The non-linear phenomenon is modeled by generating signals that have physical characteristics as ferroresonance. The ferroresonance behavior in the frequency and time domain is observed with Continuous Wavelet Transform (CWT). Spectral analysis methods are employed to single-phase voltage (Phase R) of the power grid under study, and the simulation results are sufficient to denote the frequency properties. Based on the results of power spectral density and CWT applications, the ferroresonance phenomenon is decided from the emergence of the inter-harmonics of values from 100 to 200 $\pm$ Δf to 200$\pm\Delta$f and over voltage changes.

Gharehpetian et al. in [14] determined the effect of Metal Oxide Varistor (MOV) on several various types ferroresonance considering chaos mode, subharmonic mode, and fundamental feroresonance generated in electrical networks. The authors in their paper used the chaos theory to analyze the effect of the MOV. Bifurcation, time-domain simulation, and phase-plan diagram are implemented in the investigation of this effect. The suggested power network comprises a power transformer that is lightly loaded or operated without load. The transformer core loss is modelled considering the transformer flux, while the magnetization curve is modelled on the basis of a two-term single objective polynomial. The paper also studied the suppression influence of the MOV on chaotic ferroresonance mode in the power transformer. The simulation results indicated that using MOV with power transformer has a significant suppression influence on the ferroresonance phenomena.

Fordoei and Absari et al. in [15] proposed a new method to eliminate and dampe ferroresonant oscillations in electrical power transformers. A Fault Current Limiters (FCL) of Inductive Superconducting (IS) type is applied for eliminating chaotic-ferroresonance fluctuations alongside implementing the current limiting capability of the ISFCL. The ferroresonance is considered as non-linear mathematical dynamics, and the chaos theory is implemented. Parameter changes of the system which follows chaotic ferroresonant fluctuations are investigated and analyzed using chaos theory. The system dynamic and behavior is indicated with and without implementing the ISFCL via bifurcation and phase plane diagrams. The simulation results obtained powerfully indicated the effectiveness of utilizing the proposed method for damping and eliminating ferroresonant fluctuations.

Mikhak-Beyranvand et al. in [16] investigated the thermal and electro-magnetic behaviors of the power transformer in case of ferro-resonance occurrence. A three-dimensional finite element dynamic model is used in the introduced investigations. The Jiles-Atherton (JA) mathematical model is implemented to model the hysteresis loop of the transformer core. The 1-ph transformer behavior with the subharmonic ferroresonance mode and the fundamental mode is simulated on the basis of the suggested method. The simulatin results were compared with the experimental results. The authors also developed in their paper a thermal equivalent circuit-based losses in the simulated transformer and consequently the temperature rise is evaluated during ferroresonance.

Al-Anbarri et al. [17] introduced investigations of the impacts of iron loss non-linearity in the rise of chaotic mode ferroresonance. The authors also studied the duration period of the transient chaos in an electrical power transformer. A 635.1 kV, 50 MVA power transformer is chosen for investigation. The magnetization behavior of the selected power transformer is modelled and simulated implementing a two-term polynomial of a single-objective value type. The core loss of the selected transformer is modelled and simulated using power series of third order degree type. In the nonlinearities included in the core loss three influences are obvious: (a) shorter period of duration of transient chaos, (b) onset of chaos with higher values of the opened phase voltage, and (c) less capability to ‘ jump’ phenomena.

Ben-Tal et al. in [18] introduced an approach to find ferroresonance occurrence domains. A bifurcation diagram and the Galerkin method are implemented to calculate steady-state solutions. Well-defined continuous domains are evaluated using the proposed approach. Two typical systems are used in the study. Stability investigation is carried out to distinguish between unstable and stable conditions. Comparison between experimental and computational results are indicated.

Walker et al. in [19] introduced the investigation of ferroresonance phenomenon effects on the low loss DT under various cable lengths. The simulated dynamic model was realized using ATP-EMTP software. It is proved that frrroresonance fluctuations can arise in the network due to 2-phase opening or 1-phase switching. The results obtained indicated that the overvoltage under frroresonance increases with increased cable lengths. In addition, the critical lengths of the cable under the effects of the ferroresonance phenomenon are determined. Cazacu et al. in [20] investigated the ferroresonance phenomena that takes place at the capacitive part of a small rating iron-core type power transformers used in the low voltage installations. A method for estimating the ferroresonance is proposed in this paper. The computation approach essentially depends on the numerical solution for the non-linear differential relations that dynamically model the transient characteristics. The magnetic characteristics for the implemented transformers is adequately designed using a polynomial equation of high order, which accurately models the applied device response also in high saturation areas. The authors in this article predicted and critically examined the current and voltage waveforms of the implemented transformer. The suggested ferroresonance estimation method can be enhanced in terms of both applicability and accuracy by implementing an innovative hysteresis model for the core properties of the transformer. Additionally, supplied voltage distortion of the power transformer, caused by strong nonlinearity in loads, is to be established and might also be considered.

Gharehpetian et al. [21] focused on ferroresonance affects the Distribution Power Networks (DPN) integrated with DG. The authors of this article determined the influence of different types of DG-type interconnection transformers on unbalanced and balanced ferroresonance. A PSCAD/EMTDC software is applied to perform the studies via a digital computer simulation methodology.

Esmaeili et al. [22] focused on ferroresonance in DPNs integrated with DG after islanding. In this paper, the authors studied and analyzed three types of different DGs which are synchronous machine-based DG, inverter-based DGs, and induction machine-based DG. A PSCAD/EMTDC software was applied in performing the studies via a digital computer simulation methodology. The study verified that the synchronous based-DGs and induction based-DGs are vulnerable to ferroresonance occurrence, while the inverter-based DGs have superior operation with ferroresonance.

Negara et al. [23] studied the influence of the asymmetrical distribution in flux in a 3-phase power transformer of 150/20 kV on the ferroresonance. An ATP/EMTP software was used for simulating the ferroresonance features of the symmetrical hysteresis flux of the selected transformer, and its results were compared with those of unsymmetrical. In the case of symmetrical condition, the obtained simulation results verified that the overvoltage under ferroresonance reached the value 389.81 kV on the high voltage side and 23.54 kV on the low voltage side. The current response indicated that the current on both the high voltage and the low voltage sides increased up to 1516.6 Amp & 2040.1 Amp, respectively. In the case of an unsymmetrical condition, the overvoltage reached higher values of about 2.27 % then in the symmetrical case. Various ferroresonance characteristics appeared on the power transformer with lower flux hysteresis as one leg of the transformer operates in its saturation zone.

Ferroresonance has been extensively studied and it appears from the studies already mentioned that it occurs often across the entire power system. However, the DS does not meet expectations in terms of its eagerness to study this phenomenon. Athough the DS is considered to be the zone most affected by load changes, variations in these loads can disrupt the network architecture and force the system to be exposed to ferroresonance. The increased usage of DG in DSs has certain consequences for ferroresonance, but these concerns have not received much attention.

As a result, the focus of this paper is the investigation and modeling of the ferroresonance affects the DS and how DG penetration affects it. In this paper, a High Ohmic Reactor (HOR) as a Shunt Limiter (SL) (i.e. HOR-SL) is proposed as a ferroresonance mitigation technique. This approach is a negative sequence-based detector scheme. The proposed HOR-SL method is compared with the Series Resistance (SR) and Series Tuned LC Limiter (STLCL) methods. The study is simulated by PSCAD/EMTDC.

The primary contributions of this paper are summarised as follows:

A. The contribution of DG to the decrease in the ferroresonance investigation in the distribution zone is introduced.
B. The ferroresonance phenomenon is modelled with the help of PSCAD/EMTDC software.
C. A novel method for reducing ferroresonance using the HOR-SL is introduced.
D. The proposed HOR-SL method is compared with the SR and STLCL methods used in the literature.
E. Proving the effectiveness of the proposed HOR-SL, implementing the proposed method in various case studies, for suppressing ferroresonant oscillations to create a stable orbit in the distribution network.

The remainder sections of the paper are structured as follow: Section II discusses ferroresonance mode, its definition, the causes ferroresonance, and its problems. Section III introduces the simulation cases. Section IV introduces the HOR-SL as a new method for ferroresonance mitigation, compares the proposed method with the SR and STLCL methods, and demonstrates its mechanism of control. The conclusion of paper is given in Section V.

II. FERRORESONANCE PHENOMENON

The word "ferroresonance" describes a particular type of resonance between the characteristics of an electrical network and a component containing ferromagnetic material, like a transformer or an inductor. Ferroresonance is an unanticipated phenomenon that results from the combination of nonlinear inductance and system capacitance [24]. It is a nonlinear phenomenon that resulted in energy fluctuation between a capacitive device and nonlinear inductive element. The system jumps from a stable response to a stationary-ferroresonant respomse as a result of this phenomenon [7].

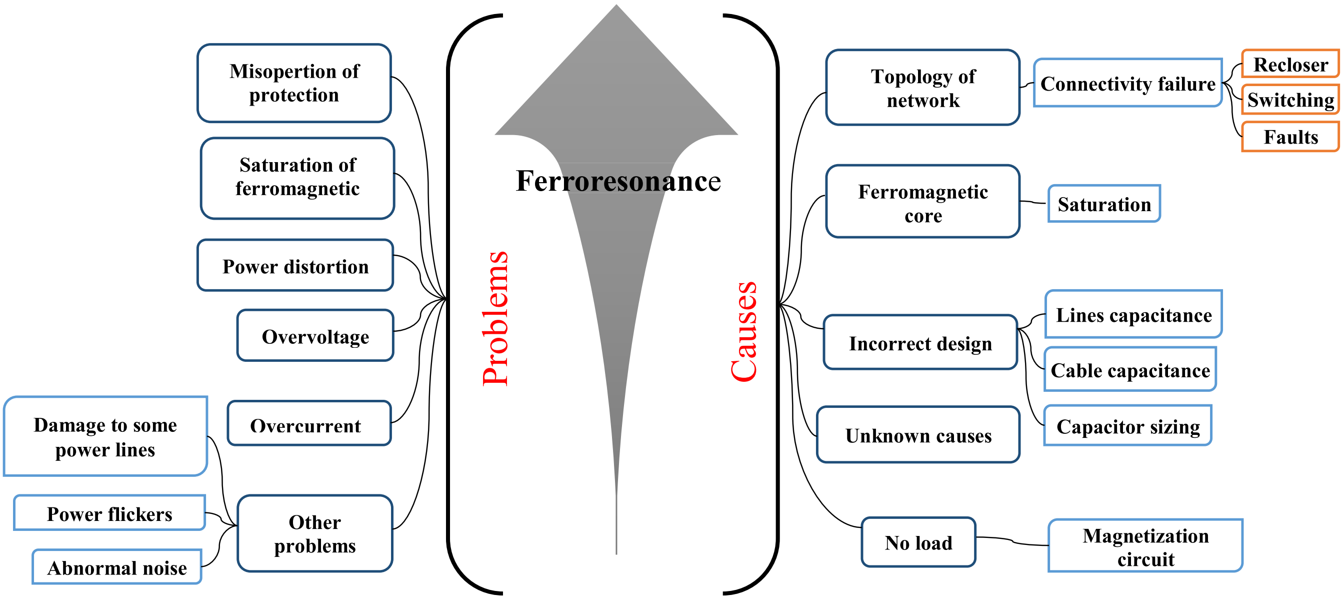


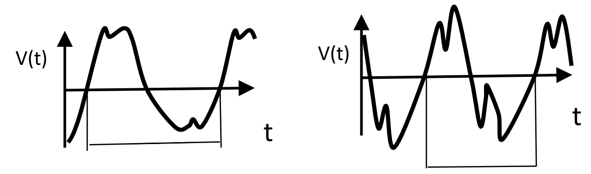
FIGURE 1. **Ferroresonance problems and its reasons.**

As illustrated in Figure 1, it causes a several of problems. Even now, it is a troubling phenomenon [12]. Prediction of this phenomenon is challenging as it might happen with only minor changes in network parameters. Due to the numerous variables that could affect ferroresonance occurrence and its sensitivity to even very slight changes in the characteristics of the power grid, ferroresonance investigation is a challenging task [25].

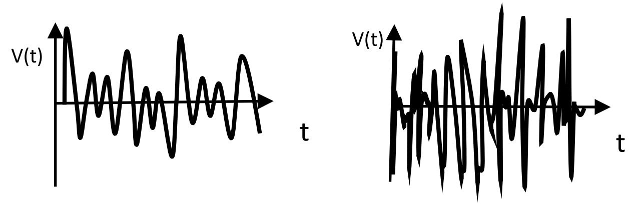
Unlike ferroresonance, resonance is considered to be a predictable phenomenon that arises from the interaction of inductance and capacitance components. The ferroresonance effect is caused by a variety of factors. The topology of the network, the incorrect design, the ferromagnetic material-core of the power transformer and other undefined reasons are the main causes. Their estimated percentage (%) of occurance is provided in Table 1 [26]. Figure 1 provides a summary of ferroresonance sources and problems [27].

There is no doubt that ferroresonance results from the interaction between the capacitance of the system and the nonlinear inductor. The occurrence of an abnormal change in the electrical network triggers the system to enter a ferroresonant state. As listed in Table 1, several factors could be at the root of this issue, including:

- System design: Numerous components, such as cables, switches, transformers, capacitors, and transmission lines (TLs), make up the electrical system. A non-optimal location or an incorrectly estimated part size may result in an equivalent capacitance or inductance that is not indicated, both of which are essential elements of the ferroresonance issue. Having both components, capacitance, and inductance, makes it easy to trigger the system into ferroresonance [28].
- No load condition: In the absence of a load, ferroresonance is possible, particularly in transformers. With respect to the shunt capacitance of the primary line, it will be assumed that the coupling capacitances of the transformer from phase to ground, phase to phase, and from primary to secondary are sufficiently low to allow for their disregard. The coupling capacitances of the transformer however become more significant at voltage levels beyond 15 kV. Therefore, their contribution to the ferroresonant circuit cannot be ignored [29].
- Ferromagnetic core: The hysteresis effects and magnetic couplings of the ferromagnetic material resulted in a non-linear induction phenomenon. The ferroresonance investigation is also influenced by the magnetic cross-coupling of the flux interactions of the core legs, asymmetry, and core architecture [30].
- Topology of network: various electrical network topologies caused by cases of abnormal switching, system



(a) Fundamental ferroresonance (b) Sub-harmonic ferroresonance



(c) Quasi-periodic ferroresonance (d) Chaotic ferroresonance

FIGURE 2. **Ferroresonance modes.**

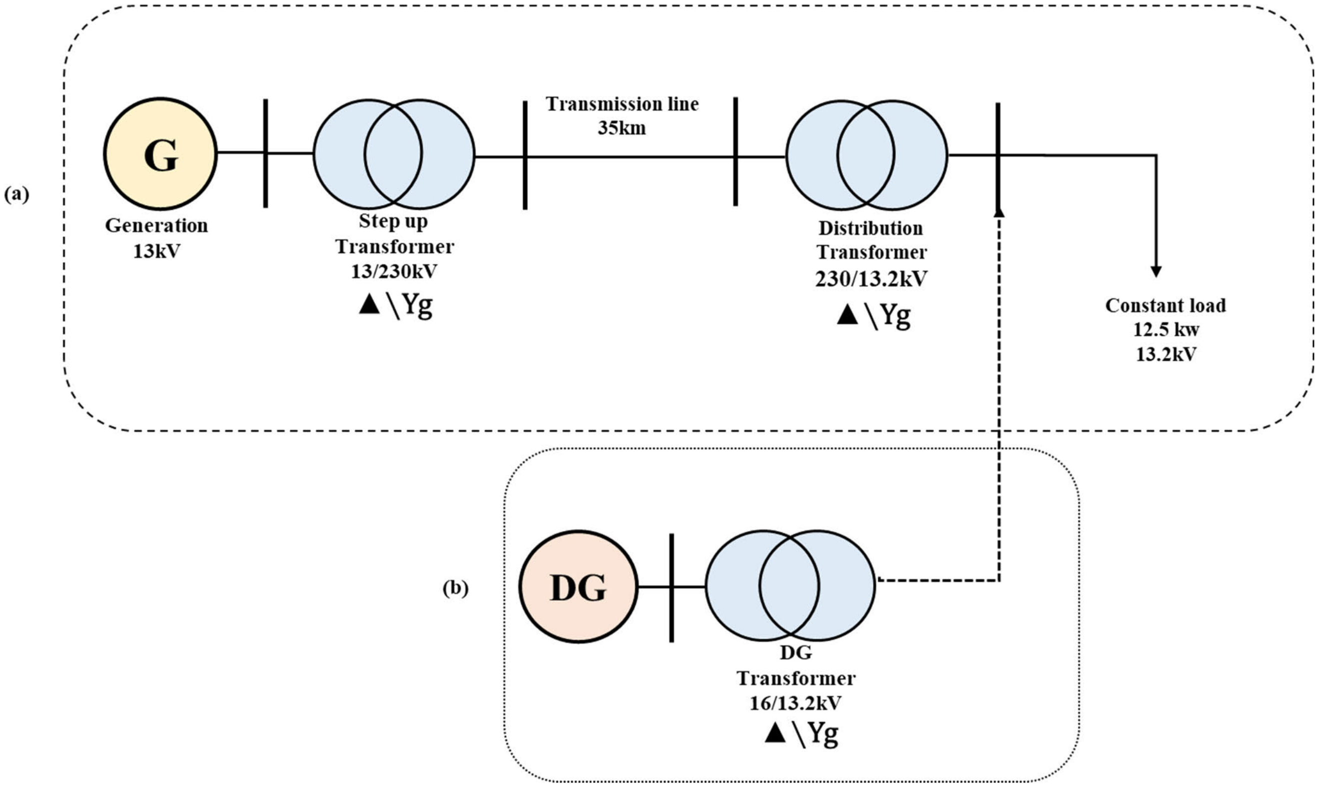


FIGURE 3. System line diagram (a) System equivalent circuit, (b) DG with the power system.

faults, and integration of parts of the electrical network such as DG units and the smart grids, lead to a change in the equivalent coefficients of the electrical network. Thus, a small change in network parameters could be the catalyst for a sharp jump that eventually results in the ferroresonance response [31], [32].

- Unexplained Causes: Due to the ferroresonance complexity and non-linearity, certain breakdowns that go unaccounted and puzzling are classified as ferroresonance [10].

Four modes of ferroresonance can be distinguished: the fundamental, the subharmonic, the quasi-periodic, and the chaotic modes. The wave in the fundamental mode has the same frequency and period as the power system but contains odd harmonics as shown in Fig.2-a. The wave in the subharmonic mode exhibits distortion due to subharmonics and has a period multiple of the source period (nT), as illustrated in Fig. 2-b. The wave in the quasi-periodic mode, as shown in Fig. 2-c, is not essentially periodic but instead adopts a tentative shape as a result of the blending of multiple frequencies. The wave in chaotic mode is nonperiodic and lacks a defined shape, as illustrated in Figure 2-d [33].

TABLE 1. Main reasons lead to ferroresonance.

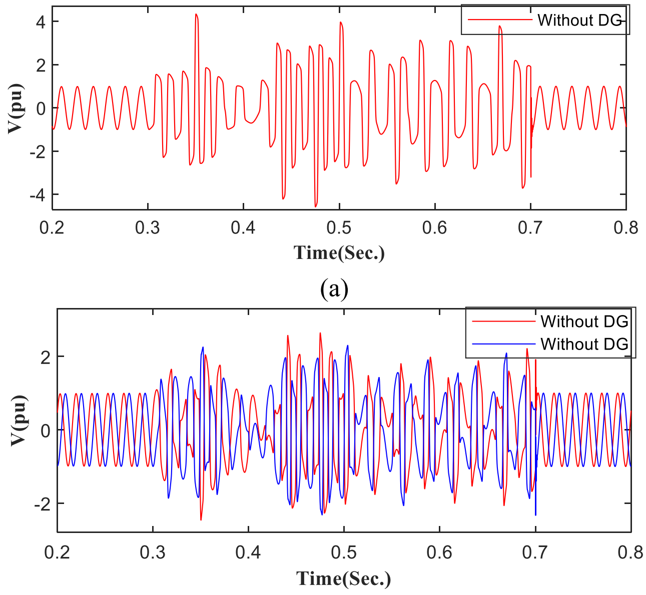
Reason of occurrence	Estimated percentage of occurrence
Incorrect design	**30 %**
No load condition	**25 %**
Ferromagnetic core of transformer	**20 %**
Topology of network	**15 %**
Unexplained causes	**10 %**

Consequently, to prevent its serious technical and financial problems, researchers concentrated on lowering the prevalence of this phenomena. According to [26], a resistor with two back to back one way adjustable switches was used on the secondary of the transformer. It acts like a damping resistor (R) to reduce ferroresonance. Reference [34] provided the use of a damping resistor linked to the secondary side of the transformer for reducing ferroresonance effects.

Also, [35] designed a resistance (R) with an electronic switch, linked on the secondary of the transformer, to mitigate the ferroresonance. A control schem is preented to control the operation of the switches. The conduction of R is controlled through a saturable-voltage reactor or mechanical switch. In the event of ferroresonance, the saturable reactor becomes saturated and ferroresonance can be reduced by resistance.

Additionally, to mitigate ferroresonance, [36] applied a Shunt Reactor (SR) in the secondaryof the tramsformer. As a minimization of ferroresonance on a power TL, thyristor-driven spontaneous close SRs were presented in [37] which shortens the duration time of high voltage that results from ferroresonance.

A gas lamp based on gas discharge that was coupled to the secondary side of the CVT was introduced in [38] as a



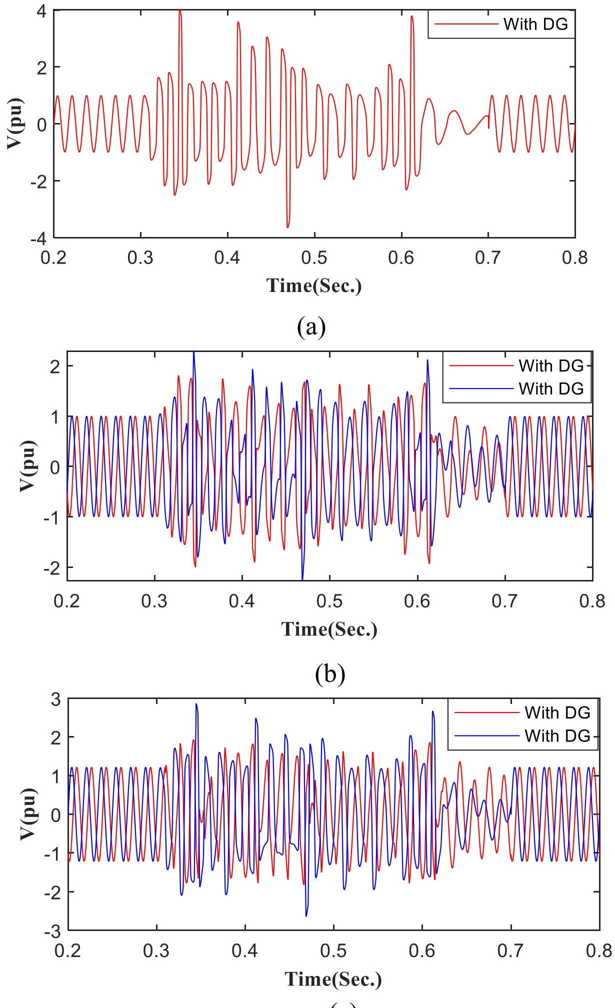
(a)

(b)

FIGURE 4. **Ferroresonance occurance in DS without DG: (a) HV side (Phase B); (b) LV side (Phase A & B).**

TABLE 2. **DG transformer data.**

DG Transformers Model	
Connection method	Δ / Y
Voltage (line rms)	16 / 13.2 [kV]
Rated power	30 [MVA]
Leakage reactance	0.08 [pu]
Copper losses	0.0084 [pu]
No-load losses	0.005 [pu]



(a)

(b)

(c)

FIGURE 5. **Ferroresonance occurance in DS with DG; (a)) HV side (Phase. C; (b) LV side (Phase B & C), (c) DG side (Phase B & C).**

ferroresonance eliminator element. A ferroresonance limiter composed of a damping resistor linked with a controllable thyristor prevented a chaotic ferroresonance caused by capacitors connected in series with the CVT reported in [39]. Reference [40] presented a design for two ferroresonance mitigation circuits linked to the CVT secondary side. The first method used only a resistance, and the second involved an RLC circuit. In [41], it was recommended that a resistor bank or damping reactor be linked to the secondary side of the transformer, which serves as a ferroresonance suppuration method. The converter design described in [42] was intended to reduce ferroresonance oscillation by implementing damping resistor emulators. A clever ferroresonance limiter circuit with four magnetically connected windings was proposed in [43]. The PT is connected in parallel with the primary winding. An eliminated ferroresonance overvoltage value is achieved through the use of the secondary winding.

III. FERRORESONANCE CASE STUDIES

In this section, two case studies are introduced to model and investigate the ferroresonance. Morever, the effect of DG on this phonomenon is discussed in this section.the two case studies are provieded in iFigures 3-a and 3-b. The first case is the ferroresonance investigation in the DS shown in Figure 3-a. The second case study discusses the investigation of ferroresonance in the DG, which was integrated with the DG as shown in Figure 3-b. The DS fed from the TL of the overhead-type coming from the generator plant, as indicated in Figure 3-a, can be thought of as the equivalent circuit diagram of the electric power system.

The system under study in the first case is functioning normally, but if the sending side of the TL was to be severed, the transformer voltage fluctuates sharply on both transformer sides as shown in Figure 4. The inductance of the DS and the TL capacitance interact. When one conductor of the TL phases is broken, a chaotic ferroresonance is investigated on the transformer sides, as illustrated in Figure 4. This result verifies the modes explained in the section II. On the high voltage side, the voltage value increased by more than 4 pu, and on the low voltage side, it increased by more than 2.7 pu.

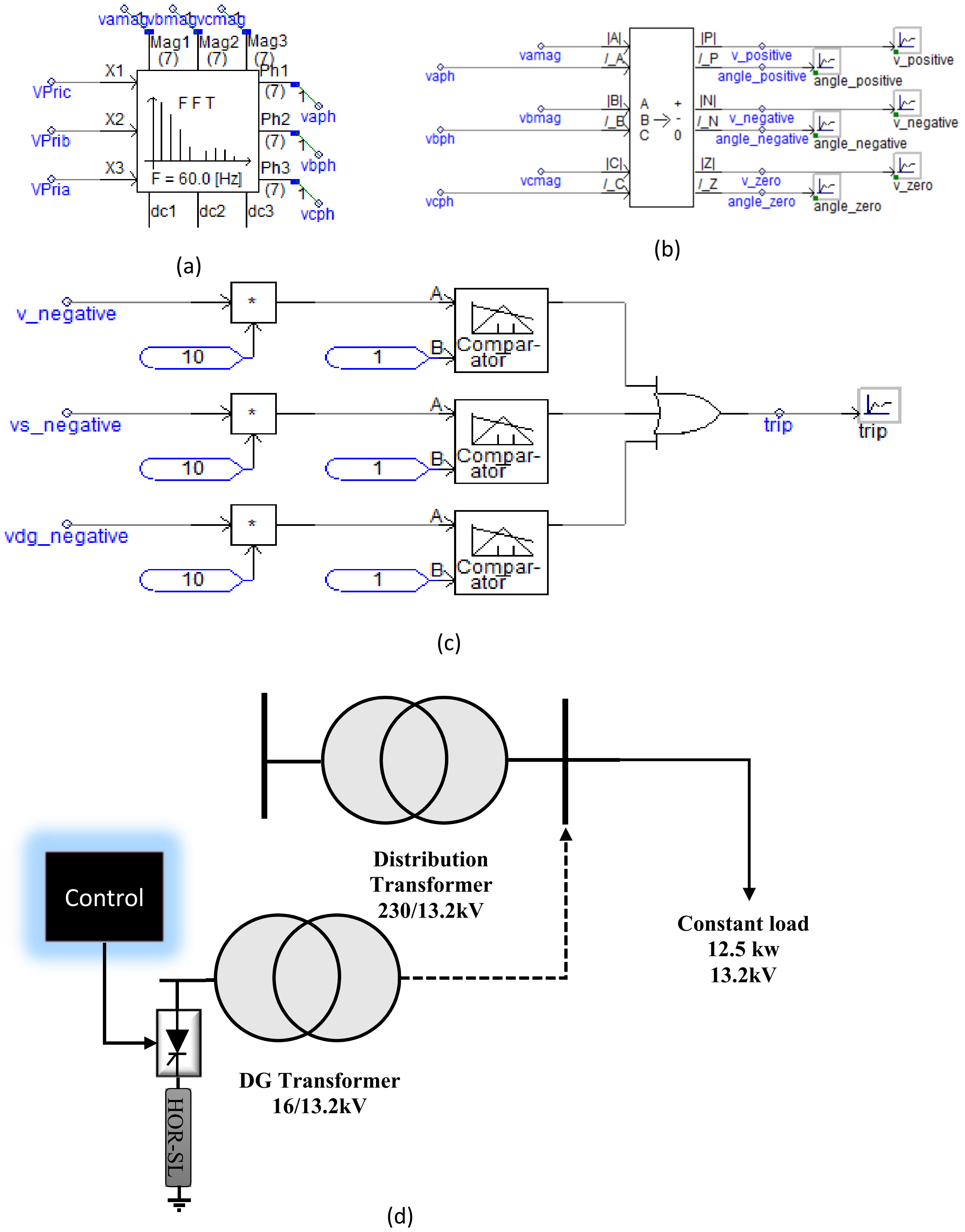
To study the effect of DG on the ferroresonance, the DS is penetrated using a DG unit as indicated in Figure 3-b. In the PSCAD/EMTDC simulation, the Unified Magnetic

TABLE 3. Maximum voltage values and mitigation instants of time implementing the STLCL, Series resistance, and HOR-SL methods.

	DS Without DG											
Max. voltage value (pu)	**High voltage side**											
	Phase A				**Phase B**				**Phase C**			
	Without	With HOR-SL	With STLCL	With SR	Without	With HOR-SL	With STLCL	With SR	Without	With HOR-SL	With STLCL	With SR
	🟩	🟩	🟩	🟩	4.5	1	4.4	4.25	🟩	🟩	🟩	🟩
	Low voltage side											
	Phase A				Phase B				Phase C			
	Without	With HOR-SL	With STLCL	With SR	Without	With HOR-SL	With STLCL	With SR	Without	With HOR-SL	With STLCL	With SR
	2.6	1	2.5	2.3	2.3	1	2.5	2.3	🟩	🟩	🟩	🟩
Mitigation instant time (m Sec)	**High voltage side**											
	Phase A				Phase B				Phase C			
	Without	With HOR-SL	With STLCL	With SR	Without	With HOR-SL	With STLCL	With SR	Without	With HOR-SL	With STLCL	With SR
	🟩	🟩	🟩	🟩	🟥	17.8	100	150	🟩	🟩	🟩	🟩
	Low voltage side											
	Phase A				Phase B				Phase C			
	Without	With HOR-SL	With STLCL	With SR	Without	With HOR-SL	With STLCL	With SR	Without	With HOR-SL	With STLCL	With SR
	🟥	17.8	100	125	🟥	17.8	100	110	🟩	🟩	🟩	🟩
	DS integrated with DG											
Max. voltage value (pu)	**High voltage side**											
	Phase A				**Phase B**				**Phase C**			
	Without	With HOR-SL	With STLCL	With SR	Without	With HOR-SL	With STLCL	With SR	Without	With HOR-SL	With STLCL	With SR
	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	4	1.3	1.2	4
	Low voltage side											
	Phase A				**Phase B**				**Phase C**			
	Without	With HOR-SL	With STLCL	With SR	Without	With HOR-SL	With STLCL	With SR	Without	With HOR-SL	With STLCL	With SR
	🟩	🟩	🟩	🟩	1.9	1	1.2	2.2	2.28	1	1.13	2.4
	DG side											
	Without	With HOR-SL	With STLCL	With SR	Without	With HOR-SL	With STLCL	With SR	Without	With HOR-SL	With STLCL	With SR
	🟩	🟩	🟩	🟩	1.9	1	2.9	2.1	2.8	1.2	3.8	2.9
Mitigation instant time (m Sec)	**High voltage side**											
	Phase A				**Phase B**				**Phase C**			
	Without	With HOR-SL	With STLCL	With SR	Without	With HOR-SL	With STLCL	With SR	Without	With HOR-SL	With STLCL	With SR
	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	30	40	107
	Low voltage side											
	Phase A				**Phase B**				**Phase C**			
	Without	With HOR-SL	With STLCL	With SR	Without	With HOR-SL	With STLCL	With SR	Without	With HOR-SL	With STLCL	With SR
	🟩	🟩	🟩	🟩	🟥	22	33	100	🟥	23	50	108
	DG side											
	Without	With HOR-SL	With STLCL	With SR	Without	With HOR-SL	With STLCL	With SR	Without	With HOR-SL	With STLCL	With SR
	🟩	🟩	🟩	🟩	🟥	21	70	89	🟥	21	36	90

Equivalent Circuit (UMEC) transformer was utilized to consider the magnetic interaction between various phases. The information needed for DG transformer modeling is provided in Table 2.

A DG unit of 16kV is connected, with the standard interconnection, to the DS via a the DG transformer. The DG shares 30% of the rated load capacity and injects active power into the system. The discussed mechanism is shown in Figure 3-b. The ferroresonance phenomena is eliminated when the DS is penetrated by the DG, even if one or more conductors of the TL are disconnected from the network at any load level. The system was triggered into ferroresonance state in this case as a result of the inclusion of DG, which caused a change in the topology of the network. By examining all abnormal separations between the DG and the TL, the ferroresonance phenomenon was investigated. This occures only in one scenario in which the DG is separated with one phase (Phase A) breakdown. It resulted in chaotic ferroresonance as shown in Figure 5. It is obvious from Figure 5 that system voltage increased to the values 2.3 pu and 4 pu in the



(a)

(b)

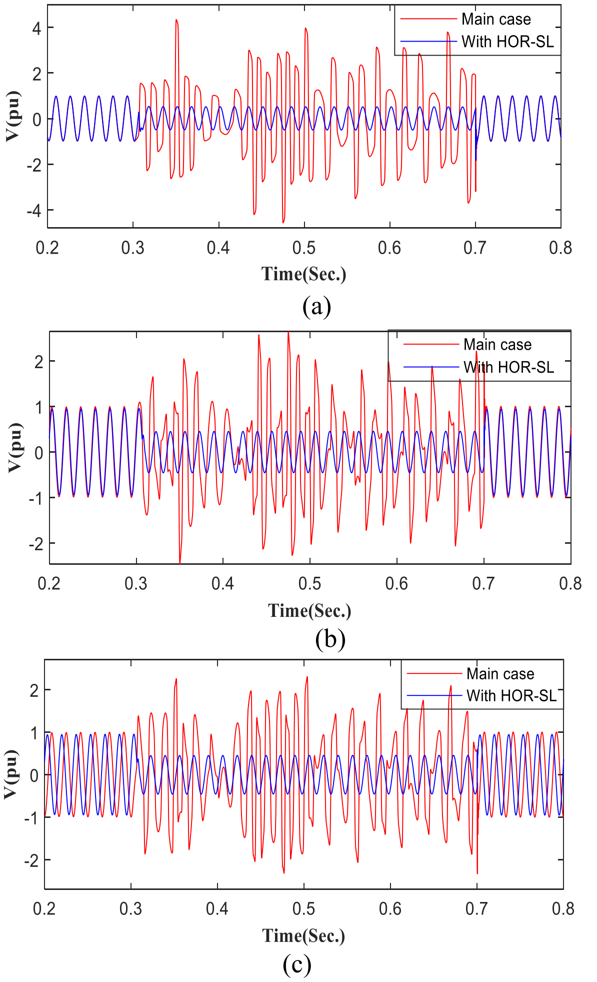
(c)

(d)

FIGURE 6. Simulation of the HOR-SL control circuit in PSCAD/EMTDC (a) FFT, (b) Sequence Filter, (c) Comparator, (d) HOR-SL position.

low voltage and high voltage sides respectively. Figure 5 also indicates that the sytem voltage increased to voltage value of 2.8 pu on the DG side.

At time instant 0.3 seconds, all separation conditions are applied and at time instant 0.7 seconds, the system recovers its original dynamics. The ferroresonance phenomenon causes extraordinarily high voltage levels that reached a value of 4 pu. The components of the power system may sustain detrimental damage as a result of abnormal switching and the unexpected conductor failure. the system protection



(a)

(b)

(c)

FIGURE 7. **Voltage signal with & without implementing the HOR-SL in the system, (a) HV side (Phase B); (b) LV side (Phase A);, (C) LV side (Phase B).**

against phase failure is crucial, for this reason. The incidence of ferroresonance can be decreased by adding DG to the radial DS, albeit occasionally the ferroresonance may get worse.Therefore, researchers must direct their efforts toward ferroresonance avoidance and optimal DG use.

IV. MITIGATION OF FERRORESONANCE

A. PROPOSED HOR-SL METHOD

HOR-SL based on a negative-sequence detector is proposed as a novel technique for ferroresonance mitigation. HOR-SL is considered as a device to be designed and inserted into the network for the purpose of limiting or suppressing ferroresonance. Figure 6 (a,b and c) depicts the HOR-SL, and the model of its control circuit using a PSCAD/EMTDC software. As a result, it is clear that no PT in the approach simulating for the suggested method on the simulation is uesd. It is composed of a HOR shunt connected to the network. Through a controllable switch that receives a controled signal comes via a negative-sequence detector device. In this control scheme, the designed HOR-SL is interconnected to the DS. Under the ferroresonance condition of the system, the negative sequence exceeds zero. The control circuit is used to gather network signals and input them into the negative sequence detector. When there are a value for the negative component, the switch is signaled to close, and when the controled signal is halted there is no value for the negative component, the switch reverts to its original state of disconnection. The negative sequence has a low value when the system starts to operate.. In the result, the negative-sequence was amplified before it is applied to the comparator, as shown in Figure 6-c. This process is designed to avoid the switch being closed at the time instant when the system is energized. After applying the proposed HOR-SL in the system suggested for the first case indicated in Figure 3-b, the voltage waveforms are indicated in Figure 7. In the transformer primary and secondary side, respectively, the ferroresonance was decreased from a voltage value of 4.2 pu to 0.6 pu and 2.8 pu to 0.6pu. Figure 7 denotes the voltage of DS in the first case study when applying the HOR-SL. Figure 8 (top part) depicts the controlling signals of negative-sequence component in the first scenario. The graphic shows the disconnection and recovery time instants besides the connection and disconnections of the suggested HOR-SL in the distribution network. The trip signal for the controlled switch is shown in the lower half of Figure 8. It is noted in Figure 8 that the time difference between the HOR-SL connection and the abnormal separation is 9.9 msec. In Figure 8 it is observed that the time difference between the HOR-SL disconnection and the recovery of the system is 17.8 msec. As a result, the suggested HOR-SL suppresses the ferroresonance before it rises to a level that put the electrical system components in risk. Figure 9 depicts a blue curve representing the voltage waveforms of the DS implementing the proposed HOR-SL scheme. It is obvious from Figure 9 that the ferroresonance was decreased from a voltage value of 4 pu to a value of 1 pu in the primary of the transformer, from a voltage value of 2.3 pu to a value of 1 pu in the transformer secondary side, and from voltage value of 2.8 pu to value of 0 pu in the side of the DG after the HOR-SL was implemented in DS

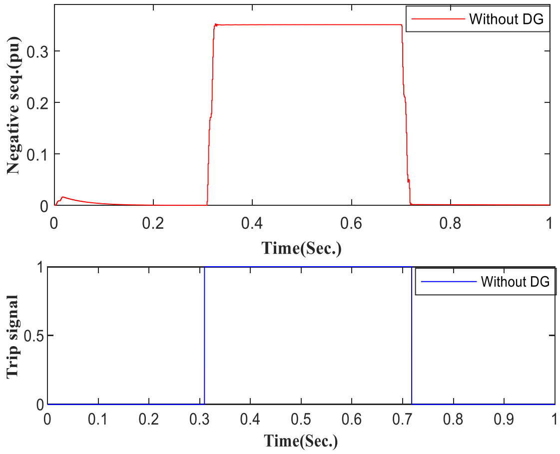


FIGURE 8. **First case Negative sequence component & its trip signal.**

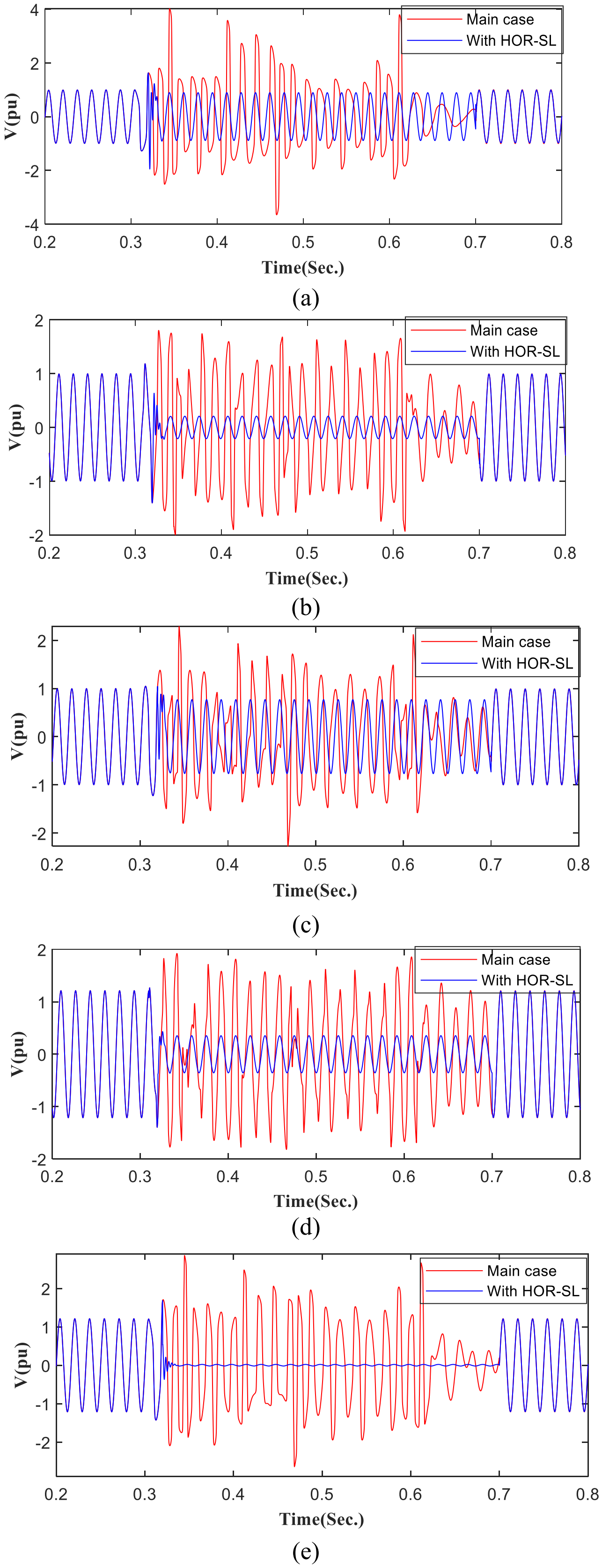


FIGURE 9. Voltage signal with & without applying HOR-SL in system penetrated with DG, (a) HV side (PhaseC); (b) LV side (PhaseB); (c) LV side (PhaseC); (d) DG side (PhaseB); (e) DG side (PhaseC).

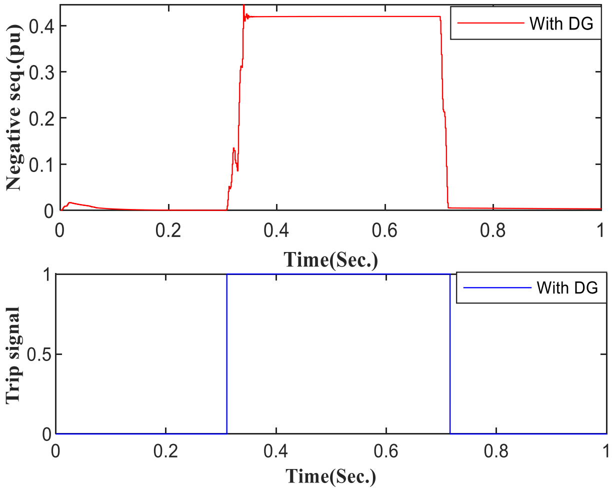


FIGURE 10. Second case Negative sequence component & its trip signal.

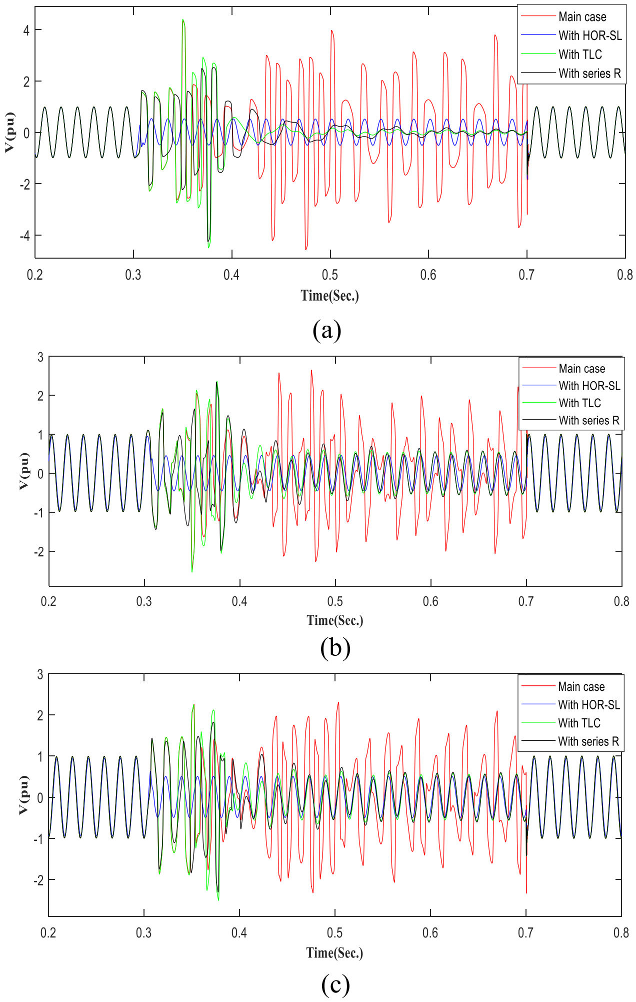


FIGURE 11. Voltage signal with implementing the STLCL; Series resistance; & HOR-SL in the system, (a) HV side (Phase B); (b) LV side (Phase A); (C) LV side (Phase B).

integrated with the DG as indicated in Figure 9. Figure 10 (top part) depicts the component of the negative-sequence of the system under study in case of DG connected to the the

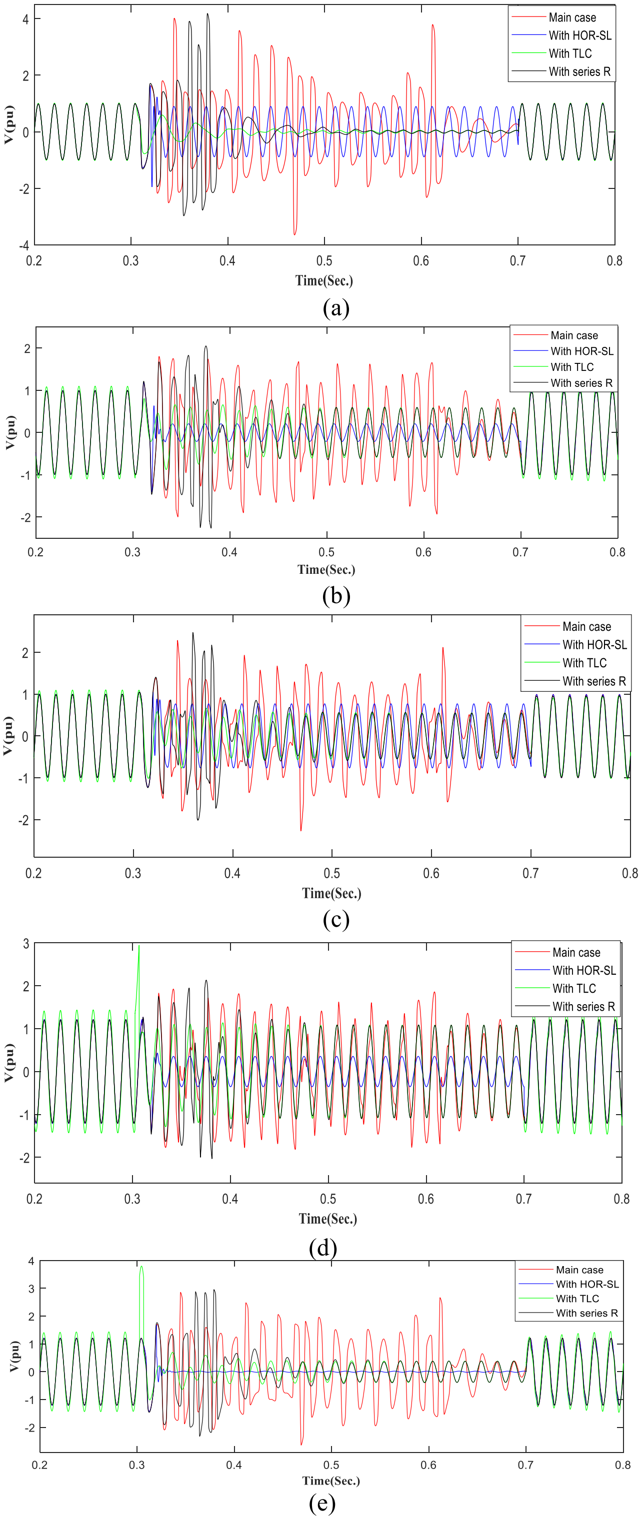


FIGURE 12. **Voltage signal with implementing the STLCL, Series resistance, & HOR-SL in the system penterated with DG, (a) HV side (PhaseC); (b) LV side (PhaseB); (c) LV side (PhaseC); (d) DG side (PhaseB); (e) DG side (Phase C).**

distribution network. The figure shows the separation and recovery instants of time besides the connections and disconnections of the suggested HOR-SL in distribution network. The trip signal for the controlled switch is shown in the lower half of Figure 10. It is clear that there is a 10.4 millisecond gap between the anomalous separation time instant and the time instant the HOR-SL is connected to the network, and there is a 15.5 millisecond difference between the recovery instant of time and the time the HOR-SL is disconnected from the network. As a result, the ferroresonance can be suppressed using the HOR-SL suggestion before it rises to a level that endangers the electrical system's components.

B. COMPARISON

The suggested HOR-SL method, explained in subsection IV-A and indecated in Figure 6, is compared with the series resistance and Series Tuned LC Limiter (STLCL) methods used in [44] and [45], respectively. The the voltage of the DS in the system studed in the first case using the proposed HOR-SL, SR, and STLCL methods are indicated in Figure 11. In second case, the sysrem voltage using the proposed HOR-SL, series resistance, and STLCL methods is indicated in Figure 12. Table 3 indicates the maximum voltage value and the time taken to mitigate the ferroresonance. In the Table, red cells indicate that the ferroresonance in this phase has not been mitigated whereas green cells indicate that there is no ferroresonance in this phase. It is concluded from Table 3 that the proposed HOR-SL is the optimum method for reducing ferroresonance. When using the HOR-SL technique, the voltage value in both cases on all phases did not surpass 1 pu. As a result, applying the suggested HOR-SL in comparison to other methods, the time needed to mitigate the ferroresonance is the minimum mitigation time. Additionally, Figures 11 and 12 demonstrate how the proposed HOR-SL contributed to the quick ferroresonance mitigation.

V. CONCLUSION

This paper discussed the ferroresonance phenomenon occures in the DS. The ferroresonance phenomenon is modelled with the help of PSCAD/EMTDC software. The implementation of a HOR-SL as a new technique to limit ferroresonance oscillations is acheived. Results indicated that DG penetration into the distribution zone actively contributes in the elimination of the investigated ferroresonance phnomenon. The ferroresonance effects are performed by the separation of the DG and one line of TL while the DG transformer is normally connected with the distribution zone. As a result of the requirement to separate many positions simultaneously, the occurrence rate of ferroresonance with the DG-integrated network is less than that which occurs with the DG-unintegrated network. The proposed HOR-SL was compared with the STLCL and SR methods. HOR-SL improved the security of the DS by preventing the voltage value from exceeding 1 pu under ferroresonance conditions. It can mitigate the ferroresonance in distributed networks within a time value that not exceeds 23 milliseconds. The suggested control scheme plays an active role in capturing the ferroresonance effect before it crosses the rated voltage. The control schematic is able to attach the HOR-SL at a time value of 0.3104 seconds before the voltage reaches 1 pu. Therefore, the ferroresonance suppression implementing the proposed approach is fast and more efficient.

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