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Journal:	*IET Renewable Power Generation*
Manuscript ID	RPG-SI-2018-0199
Manuscript Type:	Case Study
Date Submitted by the Author:	28-Feb-2018

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Keyword:	POWER SYSTEM TRANSIENTS, DISTRIBUTION NETWORKS, POTENTIAL TRANSFORMERS, POWER GENERATION

IET Research Journals

Research Article

The Institution of Engineering and Technology Journals

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ISSN 1751-8644
doi: 0000000000
www.ietdl.org

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Abstract: Power quality events associated to the occurrence of ferroresonances in MV isolated-neutral distribution power systems are well known but they still happen in nowadays grids. This paper deals with the study of ferroresonance events in a distribution grid region characterized by having to distributed generators and lightly loaded. The study shows that well-known solutions, i.e. voltage transformer damping, are difficult to apply due to legal considerations and, alternatively, the distribution system operator can take actions to minimize their effect on the distribution system. The data provided and the obtained results correspond to a three-years measurement campaign at a real MV isolated-neutral distribution power system.

1 Introduction

The occurrence of ferroresonance phenomena in distribution power systems has been observed during the last century [1] and works dealing with the phenomenon analysis date from the 1950s and 1960s [2, 3]. The electrical power systems have evolved enormously since those early days and the decentralization of power generation, i.e. photovoltaic and wind energy, and the connection of new electrical loads, i.e. electric vehicle, have completely changed the distribution power systems during the last decades [4, 5].

However, the occurrence of ferroresonances in medium voltage (MV) distribution power systems is an issue that distribution system operators (DSOs) still have to address in planning, development, operation and maintenance activities [1, 3, 6]. Early attempts to address the effect of distributed generation (DG) in the occurrence of ferroresonances are found in [7] and [8]. The provided analysis shows that power transformers in distribution electrical grids might suffer ferroresonances as a consequence of generators connected to lightly loaded feeders. The effect of diverse power transformer configurations for interconnection of DGs on the occurrence of ferroresonances is described in [9] and evaluated through simulation analysis in [10]. It is shown in [11] that a DG in island is prone to drive the ferroresonance due to the line-to-ground capacitance and the voltage transformers (VTs). Equivalent results are provided in [10]. In [12], the effects of the ferroresonance on ancillary equipment in power systems with DGs are discussed.

Ferroresonances in distribution power systems are commonly classified into four categories depending on the measured spectrum: fundamental, subharmonic, quasi-periodic and chaotic modes [13]. Moreover, in the case of VTs, two potential ferroresonances can be excited by grid side events. Breakers operation can result in series resonances [14] while line-to-ground faults energize parallel resonances due to saturation of VTs [15]. DSOs in MV isolated-neutral grids imposes the requirement that all the VTs connected to the distribution power system have to be properly damped to avoid parallel ferroresonances. This applies to the point of common coupling (PCC) of the distribution power system and the MV generator or consumer but, inside the generator or consumer installation these damping devices are not mandatory and, as a consequence, despite of having part of the connected VTs properly damped, fulfilling this operative recommendation is not ensured in all cases.

There is a variety of commercial equipments for damping purposes that improves the very basic performance of the simple damping resistor [13]. These equipments are connected to the tertiary winding of the VT, the protection one, and the literature classifies them into three categories: passive, active and electronic ones [16]. Passive equipments presents a high impedance at the nominal grid frequency, avoiding power losses in the VT while line-to-ground faults occurs. Active ones include a nonlinear element, such as a reactor, which limits the current associated to the faulty state. Electronic equipments are considered to be the fastest ones and consist of a static converter with a damping resistive load [17].

This paper studies one MV isolated-neutral distribution power system that has suffered some ferroresonance events during the last five years. Characteristics of the distribution power system, line, generators, protections, VTs and damping are provided in Section II. This section also includes the employed analysis procedure and the measurements campaign carried out to characterize the ferroresonance occurrences. The obtained measurements are provided in Section III. Finally, Section IV summarizes the conclusions of the analysis.

2 Selected MV isolated-neutral grid for ferroresonance analysis

The study of the ferroresonance phenomenon presented in this paper has been carried out for three years as a part of a research project oriented to improve the automation of MV distribution networks. Figure 1 shows one of the events registered by one of the protection equipments of a MV distribution system. The complete event was not registered due to the limited storage capability of the equipment but the plot shows the fault and the resulting overvoltage in phase B. After the fault, the system experiments a quasi-periodic ferroresonance and, due to its occurrence, one VT was damaged.

The MV isolated-neutral distribution grid, where this ferroresonance event occurred was selected as a potential target of the study. The corresponding single-line diagram is shown in Fig. 2. Two distributed generation systems based on synchronous generators are connected to this network, their nominal powers are $13.5\ MVA$ and $4.8\ MVA$ respectively. In order to carry out the study, the available details about the VTs (characteristics, damping...) employed by the

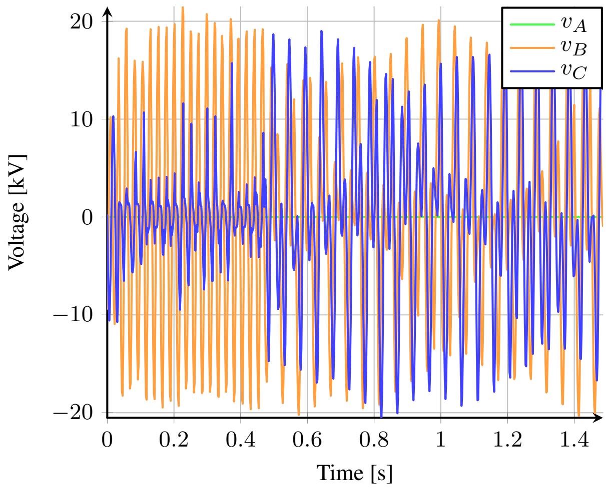

Fig. 1: Previous indicative measurements in the selected MV power system.

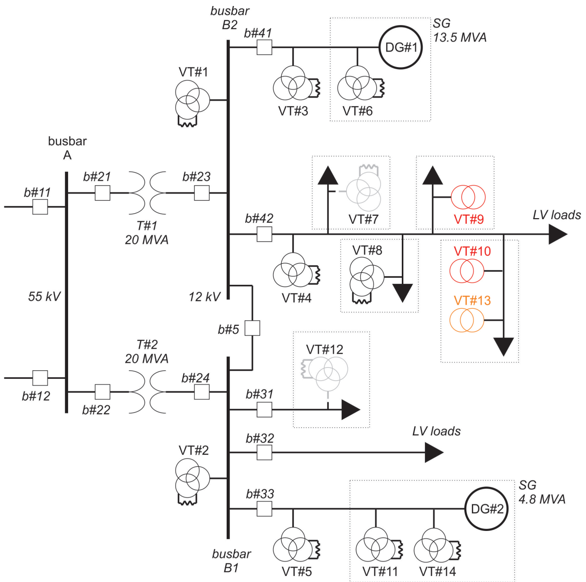

Fig. 2: Selected MV isolated-neutral distribution power system for ferroresonance study

MV customers were collected: 4 VTs were damped with 50 Ω resistors, 2 VTs connected to the same line were undamped (depicted in red) and the status of one more VT was unknown. The VTs at the DSO side were five, all of them damped with 25 Ω resistors (2). It must be also considered that VT# 7 and VT# 12 were disconnected during the measurement campaign.

The literature shows that the line-to-ground (C_g) capacitance and the magnetization curve of VTs play a key role [13] in the occurrence of parallel ferroresonances in MV isolated-neutral distribution grids. Line-to-ground faults energize the potential parallel resonances due to overvoltages occurred saturating the undamped VTs (Fig. 3). Point 1 corresponds to the normal stable operation point and while 2 and 3 represent potential ferroresonance points. In [13] these curves and the ratios X_C to $X_{L,\text{linear}}$ and X_C to $X_{L,\text{sat}}$ are employed to determine the ferroresonance risk zone of the VTs.

The capacity is sensitive to the type of line, i.e. aerial or underground, the employed isolation material and the line section, as shown in Fig. 4.

As a consequence, knowing the physical characteristics of the lines in Fig. 2, line-to-ground capacitance per line have been evaluated, the obtained results show a total capacitance of 2.77 μF for a

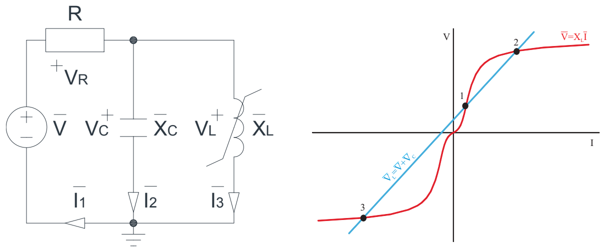

Fig. 3: Characteristic circuit for parallel ferroresonance analysis

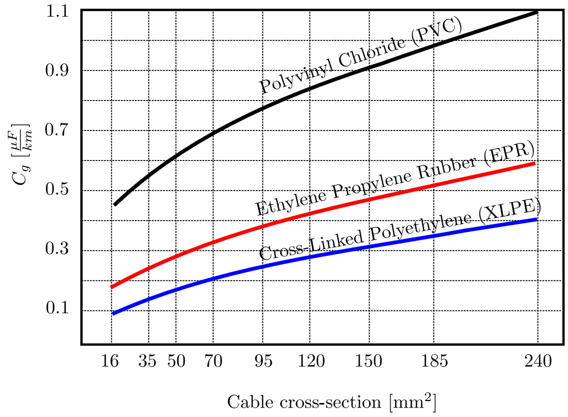

Fig. 4: Capacitance due to several isolation materials employed in lines

sum of 33.7 km of lines. Table 1 shows the values disaggregated by line.

Table 1 Line-to-ground capacitance

Line	length (km)	C_g (μF)
b# 41 line	0.498	0.34
b# 42 line	7.661	1.07
b# 31 line	6.727	0.32
b# 32 line	17.788	0.98
b# 33 line	1.02	0.06
Total	33.694	2.77

Moreover, the connected VTs in Fig. 2 were also characterized and their saturation curves obtained from manufacturers when possible and experimentally in certain cases. Figure 5 shows the magnetization curves of these transformers. From the obtained results, the saturation knees of $VT\#3$, $VT\#4$, $VT\#5$ and $VT\#9$ are the lowest one, being saturated firstly as consequence of the overvoltages during faults and ferroresonances.

3 Case Study I: Damped ferroresonance

In order to characterize the overvoltages, 4 PQ analyzers were deployed in 2015 to carry out synchronized high accuracy measurements. The selected measurement points were located in $VT\#1$, $b\#31$ line, $b\#33$ line and $b\#41$ line: two of them monitoring the DGs lines ($b\#33$ and $b\#41$ lines), one applied to one of the substation transformers ($VT\#1$) and one more applied to the line with several MV customers ($b\#31$ line), some of them without damping installed in the VTs, and LV loads. In July 2016, one fault and the subsequent ferroresonance was measured. The obtained registers are shown in Fig. 6. Figure 6. (a) represents the waveform of the voltage measured in voltage transformer $VT\#1$, Fig. 6. (b) in $b\#33$ line, Fig. 6. (c) in $b\#41$ line and Fig. 6. (d) in $b\#31$ line. A fault

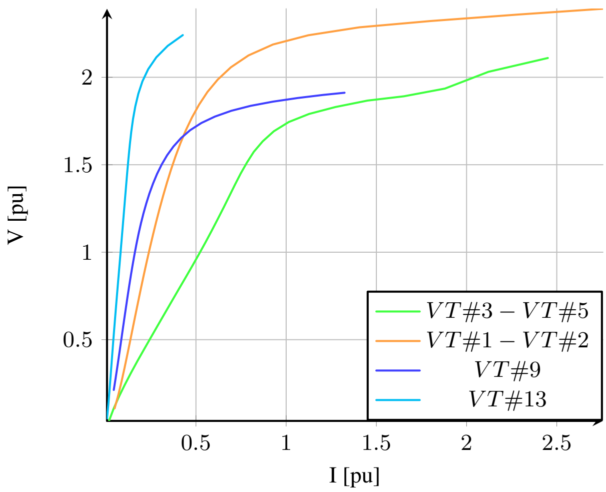

Fig. 5: Magnetization curves of the analyzed VTs

occurs at 0.06 s and, then, overvoltages are measured at all the measurement points. From Fig. 6.a the maximum measured overvoltage is 21 kV at 0.12 s, just after the fault occurrence. In Fig. 6. (d) it is observed that between 0.4 and 0.5 seconds voltage is zero, this means that this line, $b\#31$ line is open. It is achieved opening the $b\#31$. This breaker operation produce a drastically reduction of the line-to-ground capacitance, and being a lightly loaded long line, the ferroresonance conditions change and it is extinguishing in less than 1 s. This is observed in the other measurement points (Fig. 6. (a), 6. (b) and 6. (c)).

4 Case Study II: Sustained ferroresonance

During the study, the PQ analyzers were placed measuring different lines. In October 2017, a new ferroresonance event occurred and this time, the four PQ analyzers were placed in $VT\#1$, $b\#31$ line, $b\#41$ line, $b\#42$ line. Figure 7 shows the measured voltages. In this case at approximately 0.5 s a fault occurs in the system followed by a ferroresonance with maximum overvoltage of 20 kV. Figure 7. (a) and 7. (b) show that in these lines ferroresonance is damped in coincidence with the opening of $b\#5$ in busbar B1 at 4.5 s, i.e. decoupling both substation busbars. After decoupling, busbar $B2$ remains energized through $T\#1$ and $DG\#1$ and the ferroresonance in busbar $B2$ continues up to 5.2 s. Between 4.5 and 5.2 s the ferroresonant island change his behavior from the ferroresonance before 4 s. At 5.2 s $b\#23$ is opened and B2 is de-energized (Fig. 7. (c) and 7. (d)). In this case, two islands are formed with the decoupling of busbar $B1$ from busbar $B2$ but only island from busbar $B2$ keeps the ferroresonance phenomenon. The reason for this behavior is that the ferroresonant island has no damped VTs in its system.

5 Discussion

Successive occurrence of overvoltage events linked to faults in a certain area of a MV isolated-neutral distribution power system is indicative of issues related to both the design and exploitation of the affected network. To evaluate the circumstances that contribute to the appearance of these events, an exhaustive campaign compiling potentially relevant information and a previous study of the power system under analysis is required. The proper deployment of power quality analyzers and their synchronization allows diverse operation conditions to be monitored with a minimum number of measurement equipments.

This paper shows two representative cases of ferroresonance occurrence in a MV isolated-neutral distribution system where both damped and undamped voltage transformers are connected. In Case Study I, the ferroresonance damping is due to the disconnection of a line, that represents a reduction of 16 % of the installed power and a reduction of 12 % of the system capacity. This change of topology results in the extinction of the ferroresonance while maintaining the operation of the distributed resources. Establishing a policy to select the most appropriate topology change resulting in the ferroresonance damping is not trivial and not only technical considerations are evaluated.

In Case Study II, both substation busbars are decoupled once an stable ferroresonance event occurs. However, the busbar having the undamped voltage transformers experiences a maintained ferroresonance due to the energization through $T\#1$ and $DG\#1$ [11]. The busbar without undamped voltage transformers success to recover the normal operation state.

In Table 2, the increments in the significative parameters regarding ferroresonance of the system are presented. The success cases in ferroresonance damping are the Study Case I and the Study Case II from busbar $B1$. These cases have in common a low reduction of the potential loads and a compensation between capacity reduction and inductance, linear and saturated, increase. Regarding the Study Case II from busbar $B2$, in which ferroresonance phenomenon is not damping, the reduction of the potential loads are very high and capacity is reduced drastically with a medium increment of the inductances.

Table 2 Increments in the parameters of the system

	Increments (%)		
		Study Case II	
	Study Case I	From busbar B1	From busbar B2
Potential loads	-16	-34	-66
Capacity	-11,7	-50,6	-49,4
Linear inductance	0	161,5	61,9
Saturated inductance	0	120,1	83,23

6 Conclusion

This paper shows the results of a ferroresonance study carried out in a MV isolated-neutral distribution power system where both distributed generation and loads are connected. The previous analysis revealed that damped and undamped voltage transformers are connected and, hence, the power system was prone to suffer ferroresonance events. The study highlights that although DSOs have internal standards for installing damped systems; passive, active or electronic, in the VTs, the applicable regulation allows the MV customers having undamped VT installed. The existence of undamped VTs in the system jeopardize the integrity of all the system connected. To achieve a totally damped distribution system DSOs regulations have to be applied to the customers.

The study also reveals that DSOs can minimize the effect of ferroresonances by adapting trip levels and times of the protection equipments and breakers to change the distribution power system topology to facilitate the ferroresonance mitigation. Based on this approach, DSOs can study different switching strategies to extinguish the ferroresonance and minimize its effects after the occurrence.

7 Acknowledgments

This work was supported by the Spanish government under RETOS RTC-2015-4176-3, *Innovation in the automation of the isolated neutral distribution*.

The authors also acknowledge the support received from Viesgo S.L across all the activities in the project above.

The authors would also like to thank Arteche for the collaboration in the characterization of some of the voltage transformers.

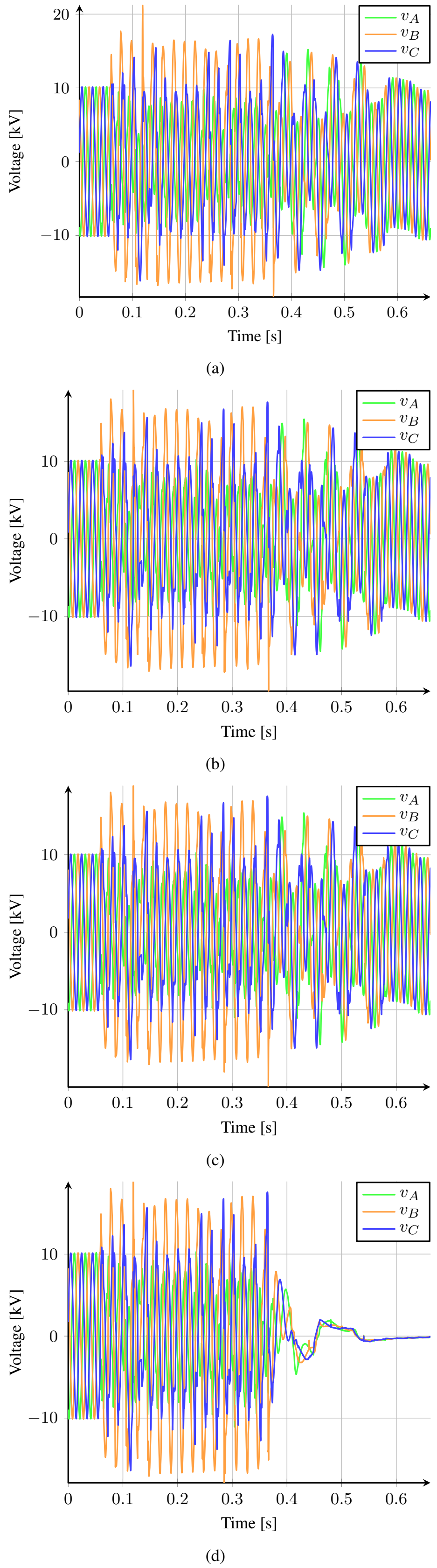

Fig. 6: Case Study I. The ferroresonance is damped by changing the line-to-ground capacity.
a Voltage waveforms at b# 23
b Voltage waveforms at b# 33
c Voltage waveforms at b# 41
d Voltage waveforms at b# 31

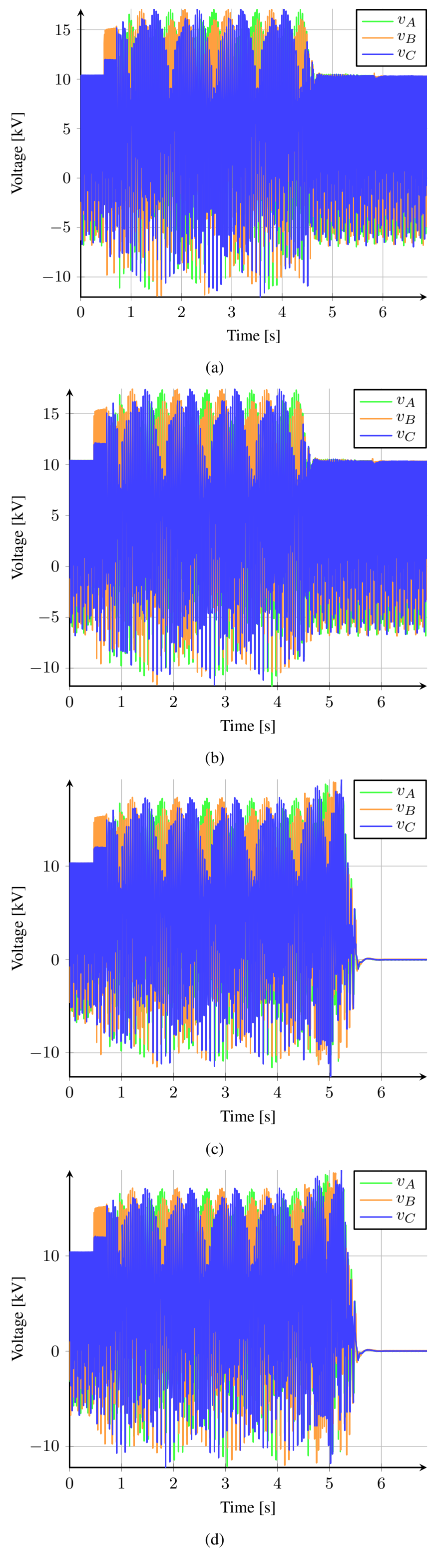

Fig. 7: Case Study II. The ferroresonance is undamped, and finishes by islanding the subsystem with undamped VTs.
a Voltage waveforms at b# 23
b Voltage waveforms at b# 31
c Voltage waveforms at b# 41
d Voltage waveforms at b# 42

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