Analysis of the transformer windings connections to reduce harmonics in electrical distribution systems.

G. Malagón, J. Blanco, G. Ordóñez, J.F. Petit, W. Giraldo and J. Chacón.

***Abstract*— This paper presents some guidelines and mitigation strategies to reduce harmonics in electrical distribution systems by applying transformers with different windings connections or phase shifting. The study of some models of nonlinear loads in distribution systems is performed, through the incorporation of transformers with different winding connections. The increase of non-linear loads in the supply network, specifically the harmonic loads, the saturation in ferromagnetic devices and the system susceptibility are the main research issues. The models of nonlinear loads and phase shifting transformers are implemented in ATP-EMTP. Case simulations with different transformer windings connections are performed on an IEEE test feeder. The conclusions show the reduction of the harmonics levels in the electrical distribution systems, specifically with the installation of Specially Connected Transformers (SCTs) and transformer with connections Dy1, Dz0 and Dy11.**

***Index Terms*—** Harmonics, Transformers windings connections, electromagnetic compatibility.

I. INTRODUCTION

Currently harmonic currents are present almost everywhere in the electrical network and are caused by the wide range of non-linear loads such as compact fluorescent lamps (CFL) [1] [2], variable frequency drives (VSD: Variable Speed Drive-ASD: Adjustable-Speed Drive) [3], three phase inverters of 6 and 12 pulses [4], personal computers [5], UPS´s or any equipment with switching power supplies (SMPS) [6], electric arc furnaces (EAF) [7], electric welders, among others. These are considered as the main source of harmonics [8] [9].

Harmonic frequencies have brought with them serious problems in the power system among which are in turn caused by harmonic currents, such as overheating and overloading of conductors (especially neutrals) [10], overheating of motors and transformers (increased losses) [11] [12], a poor power factor [13], overload capacitors used in power factor correction, skin effect in conductors, automatic tripping of protections [14] among others. Moreover problems caused by voltage harmonics, which in the case of the induction motor, generate harmonic magnetic fields in the stator with different rotation speeds and even different rotation direction, depending on whether positive or negative harmonic sequence [15]. Last, but not least, the distortion of the voltage wave, which also gives rise harmonic currents in the network [16].

G. Malagón is a PhD student in the GISEL Research Group, Industrial University of Santander, Bucaramanga, gabriel.malagon@correo.uis.edu.co.

J. Blanco is a PhD student in the GISEL Research Group, the Industrial University of Santander, Bucaramanga, jairo.blanco@correo.uis.edu.co

G. Ordóñez, J.F Petit, W. Giraldo and J. Chacón are Professors in the GISEL Research Group, Electrical and Electronic School, Industrial University of Santander, Bucaramanga, gaby@uis.edu.co, jfpetit@uis.edu.co, wgiraldop@yahoo.com and cchacon@uis.edu.co.

During the last few years, have been established some standards focused in definition, assessment, monitoring and mitigation harmonics, which are related to the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE). They have developed a wide range of publications for to allow new technological developments in the industry as well as the first steps to regulate on this issue in some countries. For example in [17] is shown how to establish design criteria for nonlinear load, while in [18] and [19] are provided the limits for harmonic current emissions for equipment with currents less than or equal to 16 A, and over 16 A respectively.

The harmonic distortion has been the cause of the deterioration of electrical machines as induction motors and transformers, being the induction motors considered as the most efficient machine for energy conversion [20]. Also the harmonic distortion increases the iron and copper losses. From this point, a number of proposals are generated that could cope with the problem by implementing some correction factors, transformers and motor derating. Thus for example in [21] is proposed a methodology for normal transformers with a nonlinear load state, but not to transformers feeding rectifiers, as in the case of [22] oriented in any type of power converter and [23] focused exclusively for the arc furnaces.

For its part in U.S, some standards have been widely accepted [24] [25] where the concept of K factor is introduced and indicates the harmonic content that can support a transformer at rated current and also it represents the additional losses in the conductors assuming, as in [21], the dependence on the square of the frequency of each harmonic.

Parallel to these methodologies in Europe are two additional methods, the first is to estimate correction factors for a standard transformer, so that the total losses do not exceed the load harmonic fundamental frequency losses (for which it is designed transformer), this quantity is called "k-factor", the second is related to the equivalent series resistance DC and AC of the transformer obtained by simulation or measurement, this factor often called the loss factor additional [26]. Likewise, for motors [27] and [28] propose methodologies for motor derating, aimed to avoid overheating the additional losses caused by product of the network harmonic distortion and voltage unbalance.

II. BACKGROUND

The problem of electromagnetic disturbance, can be defined by three elements, the first related to the source of the disturbance (in this case harmonics), the second, which would be the victim (Electrical Facility, system, equipment) and the third the coupling means between the two (Figure 1). Interference control consists to remove the source of disturbance and the strengthening of the victim, or prevent source-victim interaction through the medium [29].

VII Simposio Internacional sobre Calidad de la Energía Eléctrica 2013 SICEL

Noviembre 27,28 y 29 Medellín Colombia

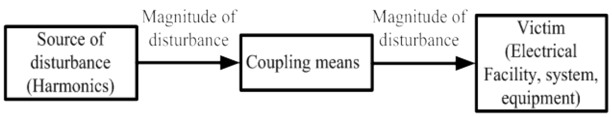

FIGURE 1 BASIC STRUCTURE OF EMC
FONT: [30]

Depending on the nature of each of the elements previously mentioned, some practices can be used for to reduce the harmful effects of electromagnetic incompatibility in the network. Thus, for control of source of disturbance can to result difficult some cases, as for example, the lightning where is not possible to control them. When the control is not possible, the interference or disturbance control should be relegated to the coupling means, where the control harmonics can be performed by implementing transformer windings connections. Often the connection type of transformers is not a relevant issue for selection of these devices, however with the problems described above about harmonics and electromagnetic compatibility, the type of connection can to allow reducing harmonic distortion and this issue is just one criteria for selection of the transformer according to the load type. The concept can be defined as positive sequence phasor, where depending on the connection type and the kind of loads, so that the harmonics of the loads may be canceled, especially when the harmonic spectrum of the loads is similar.

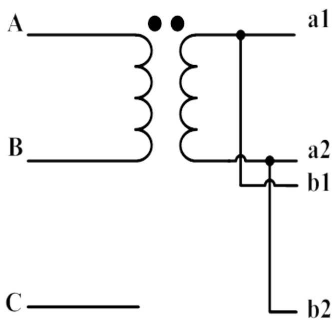

FIGURE 2. THE DIRECT CONNECTION

Also, in [31] is presented a set of Specially Connected Transformers (SCTs) that convert a three-phase source into a two-phase supply source. These transformers are used in other applications to replace the direct connection transformer (Figure 2) and thus reduce the problem of unbalanced loads caused by the railway operation. In this work, the Specially Connected Transformers are modeled and its impact is verified on harmonic propagation.

For the simulation cases performed in this work were used non-linear loads with harmonic spectra described in Table 1 and Table 2. The harmonic spectrum is typical and is taken from [14].

TABLE 1 HARMONICS SPECTRUM IN LOADS SINGLE PHASE

SINGLE- TWO- THREE PHASE, LOAD: WELDER								
1	3	5	7	9	11	13	15	17
1,00	0,296	0,088	0,02	0,023	0,023	0,011	0,004	0,009
SINGLE- TWO PHASE, LOAD: PCs								
1	3	5	7	9	11	13	15	17
1,00	0,75	0,47	0,23	0,09	0,03	0,03	0,02	0,02
SINGLE PHASE COMPACT FLUORESCENT LAMP (CFL)								
1	3	5	7	9	11	13		
1,00	0,12	0,14	0,03	0,01	0,01	0,01		

TABLE 2. HARMONICS LOADS THREE-PHASE

THREE-FASE RECTIFIER 6 PULSE										
1	5	7	11	13	17	19	23	25	29	31
1	0,2	0,132	0,073	0,057	0,035	0,027	0,02	0,016	0,014	0,012
THREE-FASE RECTIFIER 12 PULSE										
1	5	7	11	13	17	19	23	25	29	31
1	0,0192	0,0132	0,073	0,057	0,0035	0,0027	0,02	0,016	0,0014	0,0012

THREE-FASE INDUCTION FURNACE (WITH STATIC FRECUENCY CONVERTER)										
1	5	7	11	13	17	19	23	25	29	31
1	0,209	0,127	0,078	0,072	0,043	0,049	0,026	0,036	0,017	0,027
THREE-FASE DC ARC FURNACE										
1	5	7	11	13	17	19	23	25	29	31
1	0,189	0,103	0,054	0,039	0,018	0,013	0,006	0,005	0,005	0,005

Basically five types of SCT were studied in this paper, which include the classical transformer connections: V-V, Y-Delta, Le Blanc and Scott transformer, and also one recently invented: the Impedance Matching. Some applications, the V-V transformers are used in the French Train à Grande Vitesse (TGV), in the British Rail ECML [32] and Finnish state Railways [33].

Electrical schematics of the SCTs are presented below. These schematics are taken into account for generate the ATP-EMPT models and their respective simulations.

The V-V transformer is comprised of two single-phase transformers as shown in Figure 3. As mentioned above, the transformer converts a three-phase supply network to one two-phase.

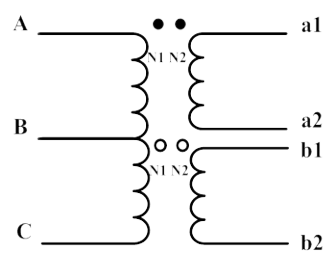

FIGURE 3. THE V-V TRANSFORMER

The Y-Delta Transformer, another specially connected transformer, consisting of three two-winding transformer (Figure 4) and is used generally in electrical distribution systems. Also, an example of specific application is showed in railways in China [34].

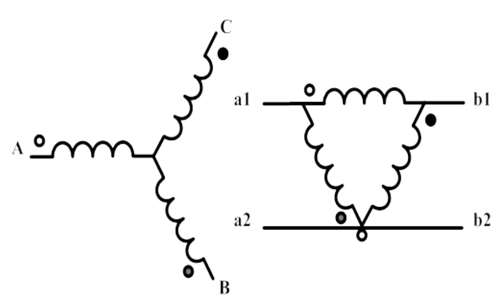

FIGURE 4. THE Y-DELTA TRANSFORMER

The Le-Blanc, one of the SCTs with the best mitigation characteristic of unbalance [31] and is utilized in railways in

Taiwan [35]. This device consists of two three-winding transformers and one two-winding transformer (Figure 5).

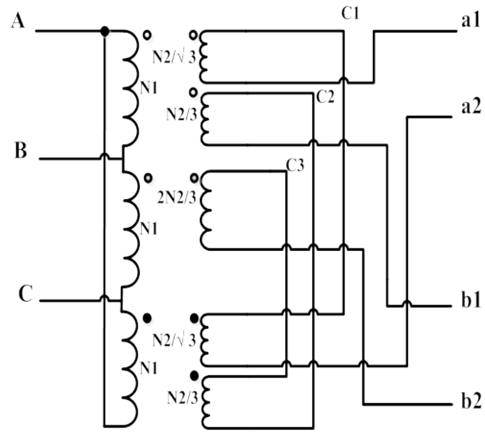

FIGURE 5. THE LE-BLANC TRANSFORMER

Additionally, the Scott transformer consists of a two-winding transformer and other of three-winding, as shown in Figure 6.

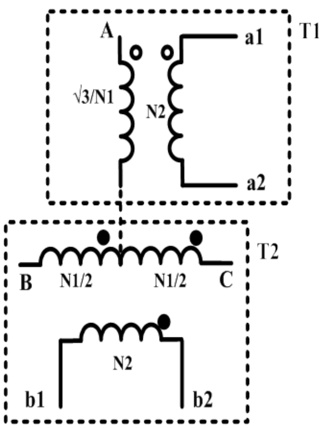

FIGURE 6. THE SCOTT TRANSFORMER

Finally, the Impedance Matching Transformer (Figure 7) is a modfied version of Y -Delta transformer and is used in railways in China. This transformer consists of two-winding transformer and other of four-winding. These extra windings provide a difference angular of 90 between two phases and also increase the current portion of the phase A to enhance the current unbalance.

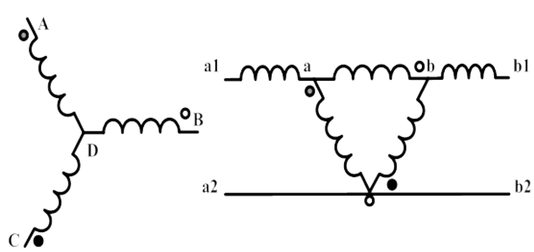

FIGURE 7. IMPEDANCE MATCHING TRANSFORMER

III. MODELING

The study is performed on a feeder 13 nodes test (Figure 9), presented by the IEEE. Red feeders will undergoing some changes that will detail later.

SCTs are used for the connection of two-phase loads. Figure 8 shows the two-phase terminals denoted as *Va1-Va2*, *Vb1-Vb2*. Phase-shifting transformers, such as Yy0, Dy1, Dy3, Dy5, DY7, DY9, Dy11 and Dz0 are used for the connections of three-phase harmonic loads in the secondary side. In Figure 8, harmonic loads are represented by the electrical currents *Iha ∡ Θha*, *Ihb ∡ Θhb*, *Ihc ∡ Θhc*.

The harmonics components of the loads are modeled in ATP-EMTP through current sources that are adjusted on a set of specific frequencies [36]. This model is composed by a current source for each particular harmonic and with a specific frequency (Figure 8). Harmonic data are taken from the characterizations given in [14], for some typical harmonic loads in power systems (Table 1 and Table 2).

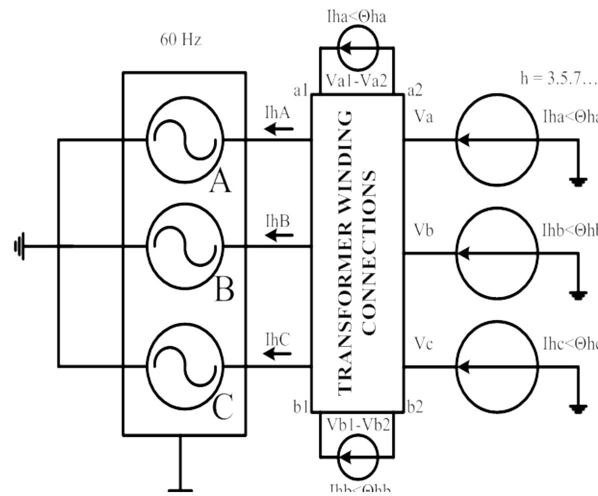

FIGURE 8. SYSTEM HARMONIC CURRENT INJECTION

For simulations, IEEE 13 Node Test Feeder was modified as follows: loads at nodes N646, N645 are concentrated as an equivalent two-phase load, connected to the node N632. Because some loads and the capacitor bank are located at the nodes N611, N684 and N652, all elements are concentrated in the node N671 as an equivalent two-phase load. The harmonic loads and their characteristics are shown in Table 1, Table 2 and Table 3. Each of these loads are connected through transformers with data presented in Table 4.

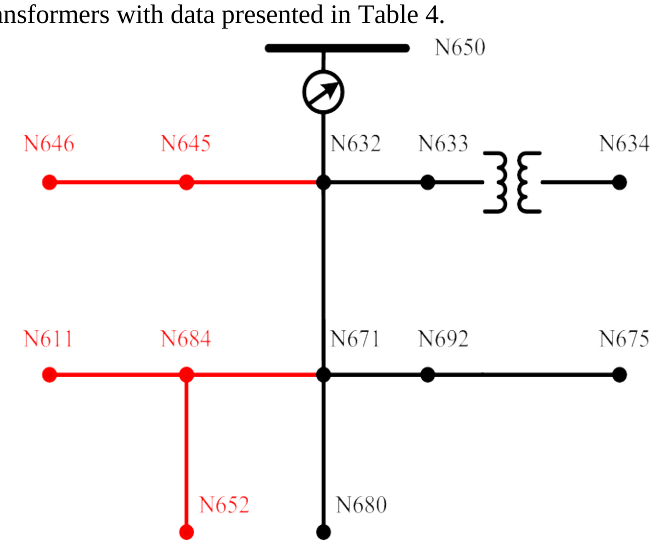

FIGURE 9. IEEE 13 NODE TEST FEEDER MODIFIED

TABLE 3. SPOT LOAD HARMONIC DATA

Node	Load Model	Ph (kW)	Qh (kVAr)	LOAD TWO-PHASE O THREE-FASE HARMONIC
634	Y-Z	400	290	THREE-PHASE, LOAD: RECTIFIER 6 PULSE (STUDY CASE 1, 2 AND 3)
632	Y-Z	400	257	TWO-PHASE, LOAD: PCs (STUDY CASE 1 AND 2)
632	Y-Z	200	116	THREE-PHASE ARC FURNACE (STUDY CASE 1, 2 AND 3)
671	Y-Z	1155	660	THREE-PHASE RECTIFIER 12 PULSE (STUDY CASE 1 AND 2)
671	Y-Z	298	66	TWO-PHASE, LOAD: CFLs (STUDY CASE 1 AND 2)
675	Y-Z	843	462	THREE-PHASE INDUCTION FURNACE (STUDY CASE 1 AND 2)
692	Y-Z	170	151	THREE AND TWO-PHASE, LOAD:WELDER (STUDY CASE 1, 2 AND 3)
675	Y-Z	843	-138	THREE-PHASE INDUCTION FURNACE (STUDY CASE 3)
671	Y-Z	298	66	THREE-PHASE CFLs (STUDY CASE 3)
632	Y-Z	400	257	THREE-PHASE PCs (STUDY CASE 3)

TABLE 4. DATA TRANSFORMER

	kVA	kV-high	kV-low	R - %	X - %
SUBSTATION:	5,000	115 - D	4.16 Gr. Y	1	8
THREE-PHASE RECTIFIER 6 PULSE	500	4.16 – Gr.W	0.48 – Gr.W	1.1	2
TWO-THREE-PHASE CFL AND PC	500	4.16 – Gr.W	0.48 – Gr.W	1.1	2
THREE-PHASE DC ARC FURNACE	250	4.16 – Gr.W	0.48 – Gr.W	1.1	2
THREE-PHASE RECTIFIER 12 PULSE	1600	4.16 – Gr.W	0.48 – Gr.W	1.1	2
INDUCTION FURNACE CFL THREE-PHASE	1000	4.16 – Gr.W	0.48 – Gr.W	1.1	2
THREE-PHASE WELDER	250	4.16 – Gr.W	0.48 – Gr.W	1.1	2

IV. STUDY CASE I

In this case, using SCT's models, each feeder has two-phase loads, located at nodes N632, N671 and N692; other loads at different nodes are connected by Dy5 three-phase transformers. Also have been assumed the following conditions:

- The magnitude of the harmonic currents is the same for each phase, *Iha = Ihb=Ihc* (Figure 8).
- The phase angles of the harmonic currents for two-phase load are assumed in phase with load fundamental current, *ϴha=ϴIa, ϴhb=ϴIb*, as shown in Table 5.

TABLE 5 STUDY CASE II: ANGLE OF THE HARMONIC LOADS

Two-Phase load	I1	I3	I5	I7	I31
Phase angle	ϴI1	3* ϴI1	5* ϴI1	7* ϴI1	31*ϴI1
Three-Phase load	I1	I3	I5	I7	I31
a	ϴV (a)	0	0	0	0
b	ϴV (b)	0	120	-120	120
c	ϴV(c)	0	-120	120	-120

To compare the harmonic degree in the transformer low side (located in N650), a harmonic maximum-magnitude cancellation index is used for SCTs:

$$M(A,B,C)_h = \left(1 - \frac{I(A,B,C)_{h-SCT}}{I(A,B,C)_{h-Direct}} x\ 100\%\right) \quad (1)$$

This index is understood as a percentage of the harmonic reduction in the primary side of the SCT compared the Direct Connection Transformer, where $I_{h-Direct}$ is the maximum magnitude of harmonic level, when the load is directly connected to the power system and I_{h-SCT} is the maximum-magnitude harmonic level when the load is connected to the power system through the SCTs.

This index shows the SCT's effectiveness in the reduction of the harmonic level for some connections type and this index is only applied in the substation (N650).

The greater the value of $M(A,B,C)_h$, the SCT is more effective on harmonic reduction. Negative values of $M(A,B,C)_h$, imply the amplification of the harmonic level by the SCT. The coefficients are calculated for phase *a*, phase *b* and phase *c* and presented in Table 6.

The index for phase *c* in some cases, has very large values for the third-order harmonics, because the index compares the third harmonic with SCT and the direct connection transformer and with this, the third-order harmonics in phase *c* will not be filtered.

TABLE 6. HARMONIC REDUCTION INDEX

Type	H-order	MAh	MBh	MCh	H-order	MAh	MBh	MCh
Yd	3	-4,75%	47,58%	-2355174,63%	19	-2,73%	-0,01%	0,00%
Im	3	10,04%	83,98%	-4077602,70%	19	-2,75%	0,01%	0,03%
V-V	3	9,35%	99,99%	-4076349,43%	19	-2,73%	0,00%	0,00%
Lb	3	-4,59%	-5,23%	-4768808,02%	19	-2,71%	0,03%	0,00%
S	3	-4,76%	-5,14%	-4879804,10%	19	-2,73%	-0,01%	0,00%
Yd	5	-93,89%	-228,61%	-78,24%	21	99,43%	-13,58%	-24,82%
Im	5	11,18%	72,16%	43,53%	21	99,60%	21,98%	14,15%
V-V	5	1,91%	72,98%	43,48%	21	99,60%	21,82%	14,26%
Lb	5	-138,3%	-75,24%	21,24%	21	99,61%	23,07%	16,22%
S	5	-138,5%	-204,79%	-57,57%	21	99,61%	-22,07%	-12,65%
Yd	7	-83,52%	-90,41%	-47,18%	23	5,28%	0,01%	0,02%
Im	7	-4,06%	47,11%	19,79%	23	5,32%	0,00%	-0,04%
V-V	7	-1,18%	44,22%	19,82%	23	5,29%	-0,02%	-0,01%
Lb	7	-113,8%	7,64%	1,77%	23	5,31%	-0,04%	0,03%
S	7	-114,0%	-70,82%	-39,53%	23	5,29%	0,02%	0,01%
Yd	9	-7,83%	43,97%	-134728,00%	25	-46,12%	-0,01%	0,05%
Im	9	16,24%	75,82%	-233265,32%	25	-46,24%	0,02%	0,01%
V-V	9	6,68%	99,95%	-233268,23%	25	-46,20%	0,02%	-0,03%
Lb	9	-7,63%	-11,52%	-277410,25%	25	-46,17%	0,06%	-0,06%
S	9	-7,81%	-8,83%	-262137,92%	25	-46,19%	-0,02%	0,03%
Yd	11	2,95%	-2,31%	5,73%	27	99,41%	-20,18%	-32,04%
Im	11	3,14%	-0,76%	4,20%	27	99,60%	30,42%	19,73%
V-V	11	1,80%	0,48%	4,22%	27	99,60%	30,40%	19,79%
Lb	11	4,48%	-0,67%	3,10%	27	99,60%	32,41%	21,75%
S	11	4,41%	-1,74%	-5,12%	27	99,60%	-32,24%	-18,19%
Yd	13	-2,49%	5,20%	2,38%	29	22,82%	0,02%	-0,06%
Im	13	-0,53%	4,85%	0,92%	29	22,90%	0,00%	0,00%
V-V	13	-0,09%	4,42%	0,87%	29	22,87%	-0,01%	0,04%
Lb	13	-0,74%	2,81%	3,33%	29	22,87%	-0,05%	0,09%
S	13	-0,88%	-4,89%	1,47%	29	22,87%	0,02%	-0,04%
Yd	15	-16,09%	39,14%	-8151,49%	31	20,35%	0,01%	-0,02%
Im	15	0,98%	97,89%	-14220,79%	31	20,35%	-0,01%	0,07%
V-V	15	-0,23%	99,77%	-14220,79%	31	20,38%	-0,03%	0,02%
Lb	15	-15,11%	-21,07%	-16532,38%	31	20,42%	0,03%	0,00%
S	15	-16,49%	-21,37%	-16412,94%	31	20,39%	0,03%	-0,01%
Yd	17	0,41%	-1,49%	-0,42%	-----	-----	-----	-----
Im	17	1,87%	0,96%	0,05%	-----	-----	-----	-----
V-V	17	1,74%	0,88%	0,04%	-----	-----	-----	-----
Lb	17	0,06%	1,15%	-0,61%	-----	-----	-----	-----
S	17	0,05%	-0,85%	-0,72%	-----	-----	-----	-----

TABLE 7 TOTAL HARMONIC DISTORTION CURRENT AT N650.

Type	THDI A	THDI B	THDI C
Yd	43,334%	49,327%	71,923%
Im	32,476%	38,552%	43,925%
V-V	33,816%	39,853%	44,274%
Lb	64,365%	44,734%	45,511%
S	55,246%	37,885%	29,434%
Dc	35,508%	48,872%	30,649%

According Table 6, the V–V connection transformer shows the best performance on the third-order harmonics reduction, while the Impedance Matching transformer has good performance on 5, 9, 15, 17, 21 and 29 order harmonics reduction. Moreover, comparing the THDI for each connection show that the best performance occurs in V-V transformer and Impedance Matching transformer, according with Table 7.

V. STUDY CASE II

In this case, the standard and non-standard connections are used, including Yy0, Dy1, Dy3, Dy5, DY7, DY9, Dy11, Dz0, Dz1, Dz2 and DZ10, and are discusses their impact on harmonic mitigation for the loads showed in Table 1, Table 2 and Table 3.

Here, some criteria are assumed as:

- Only two-phase loads are connected to the nodes without using SCT´s.
- The magnitude of the harmonic currents and the fundamental current is equal, *Iha* = *Ihb* = *Ihc*, (Figure 8).
- The phase angles of the harmonic currents are shown below in Table 8.

TABLE 8 STUDY CASE II: ANGLE OF THE LOAD HARMONIC

Two-Phase load	I1	I3	I5	I7	I31
Phase=p=a-b-c	ΘV (p)	3* ΘV(p)	5* ΘV(p)	7* ΘV(p)	31* ΘV(p)
Three-Phase load	I1	I3	I5	I7	I31
a	ΘV (a)	0	0	0	0
b	ΘV (b)	0	120	-120	120
c	ΘV (c)	0	-120	120	-120

In this case, harmonic distortions analyses are performed for each three-phase transformer on high voltage side. It is wanted to estimate the THDI before and after the transformer and identify the transformer with the best reduction harmonic characteristic.

TABLE 9 THDI CALCULATION ON CAPACITOR BANK

LOAD	CAPACITOR BANK (Node 675)		
Type	THDI A	THDI B	THDI C
Upstream of Capacitor Bank	73,8%	76,0%	75,8%
Downstream of Capacitor Bank	27,9%	27,9%	27,9%

An important case is presented to analyze the harmonic load at node 675, where a capacitor bank is connected with the load. Table 9 shows the harmonic content of the load and capacitor bank together (Upstream). Harmonic content is compared downstream and upstream of capacitor bank. The results conclude that harmonic interaction with the capacitor bank generates an increase in the THDI.

Later, in the Table 10 and Table 11, it is clear that the connection type hasn't improved the harmonic mitigation for loads without third-n harmonics. THDI was constant except for loads with third-n harmonics (three-phase welder), which are mitigated by delta connection transformers on the high voltage side.

TABLE 10 THDI CALCULATION ON TRANSFORMER HIGH VOLTAGE SIDE.

	THREE-PHASE RECTIFIER 6-PULSE (Node 634)			DC ARC FURNACE (Node 632)			THREE- PHASE RECTIFIER 12-PULSE (Node 671)		
Type	THDI A	THDI B	THDI C	THDI A	THDI B	THDI C	THDI A	THDI B	THDI C
Yy0	26,3%	26,3%	26,3%	22,7%	22,7%	22,7%	9,9%	9,9%	9,9%
Dy1	26,3%	26,3%	26,3%	22,7%	22,7%	22,7%	9,9%	9,9%	9,9%
Dy3	26,3%	26,3%	26,3%	22,7%	22,7%	22,7%	9,9%	9,9%	9,9%
Dy5	26,3%	26,3%	26,3%	22,7%	22,7%	22,7%	9,9%	9,9%	9,9%
Dy7	26,3%	26,3%	26,3%	22,7%	22,7%	22,7%	9,9%	9,9%	9,9%
Dy9	26,3%	26,3%	26,3%	22,7%	22,7%	22,7%	9,9%	9,9%	9,9%
Dy11	26,3%	26,3%	26,3%	22,7%	22,7%	22,7%	9,9%	9,9%	9,9%
Dz0	26,3%	26,3%	26,3%	22,7%	22,7%	22,7%	9,9%	9,9%	9,9%
Dz1	26,3%	26,3%	26,3%	22,7%	22,7%	22,7%	9,9%	9,9%	9,9%
Dz2	26,3%	26,3%	26,3%	22,7%	22,7%	22,7%	9,9%	9,9%	9,9%
Dz10	26,3%	26,3%	26,3%	22,7%	22,7%	22,7%	9,9%	9,9%	9,9%
Dz11	26,3%	26,3%	26,3%	22,7%	22,7%	22,7%	9,9%	9,9%	9,9%
THDI Load	26,3%	26,3%	26,3%	22,7%	22,7%	22,7%	9,9%	9,9%	9,9%

TABLE 11. THDI CALCULATION ON TRANSFORMER HIGH VOLTAGE SIDE

LOAD	INDUCTION FURNACE (Node 675)			THREE-PHASE WELDER (Node 692)		
Type	THDI A	THDI B	THDI C	THDI A	THDI B	THDI C
Yy0	73,8%	76,0%	75,8%	31,2%	31,2%	31,2%
Dy1	54,6%	55,7%	55,0%	9,4%	9,4%	9,4%
Dy3	70,9%	71,8%	70,8%	9,4%	9,4%	9,4%
Dy5	87,2%	87,1%	86,5%	9,4%	9,4%	9,4%
Dy7	70,3%	69,7%	70,3%	9,4%	9,4%	9,4%
Dy9	54,3%	54,2%	55,1%	9,4%	9,4%	9,4%
Dy11	49,6%	50,4%	50,8%	9,4%	9,4%	9,4%
Dz0	54,5%	55,7%	55,3%	9,4%	9,4%	9,4%
Dz1	50,8%	51,9%	51,9%	9,4%	9,4%	9,4%
Dz2	49,6%	50,4%	50,8%	9,4%	9,4%	9,4%
Dz10	70,8%	71,8%	70,8%	9,4%	9,4%	9,4%
Dz11	61,1%	62,3%	61,5%	9,4%	9,4%	9,4%
THDI Load	73,8%	76,0%	75,8%	31,2%	31,2%	31,2%

VI. STUDY CASE III

For the final case, the system has been modeled with only balanced three-phase loads (Table 1, Table 2 and Table 3), connected through some standard three-phase transformers described in the Case I (Section IV) and have established some scenarios.

Impact of these harmonic loads is reviewed on system boundary (substation), in the low voltage side of the transformer located at node N650. In this way, an analysis is performed where it has varied the transformer connection type in each harmonic load, initially assuming the following criteria:

- The load and the capacitor bank are accumulated as an only three-phase load on the node N675.
- The magnitude of the harmonic currents and the fundamental current, is equal, *Iha* = *Ihb* = *Ihc*. (Figure 8).
- The phase angles of the harmonic currents are shown in Table 12 and Table 13.

TABLE 12 STUDY CASE III (A): ANGLES OF THE LOAD HARMONIC CURRENTS

Three-Phase load	I1	I3	I5	I7	I31
a	ΘV (a)	0	0	0	0
b	ΘV (b)	0	120	-120	120
c	ΘV (c)	0	-120	120	-120

TABLE 13. STUDY CASE III (B): ANGLES OF THE LOAD HARMONIC CURRENTS

Three-Phase load	I1	I3	I5	I7	I31
a	ΘI (a)	3* ΘI(a)	5* ΘI(a)	7* ΘI(a)	31* ΘI(a)
b	ΘI (b)	3* ΘI(b)	5* ΘI(b)	7* ΘI(b)	31* ΘI(b)
c	ΘI (c)	3* ΘI(c)	5* ΘI(c)	7* ΘI(c)	31* ΘI(c)

For these simulations, Dy and Dz transformers are used in each harmonic load (Figure 10). In Table 14 presents the THDI calculation at the substation according to the configuration chosen in the cases *a)* and *b)* for each transformer winding connections (TWC) and also combinations of different TWC (TWCc) in the network are performed.

The THDI in the substation remains constant for different winding connections with the same harmonics phase angles. However when the harmonics phase angles are different for each kind of load (case b), the THDI in the substation is reduced, since it allows greater interaction of the different harmonics arriving in the substation node.

This greater interaction can be higher when the winding connections change for each load, as in the case of the combinations of TWC (TWCc).

The change in THDI is due to all the harmonics of same order and phase angles for case *a)*, while in the case *b)*, the load harmonics are of same order but are out of phase, thus when the harmonics flow into the substation originate a cancellation among themselves, as shown in Table 12 and Table 13.

When the harmonics are in phase as in the case *a)*, the harmonics magnitude is increased bringing a higher THDI in the substation. Conversely, when the harmonics are out of phase as in the case *b)*, the harmonics magnitude is decreasing bringing a lower THDI in the substation.

Logically, the power and the harmonic spectrum of loads are important role, since the cancellation of the harmonics will be more effective with load, power and harmonic spectrum similar.

On the other hand, if compare the results for THDI for case *a)*, with the results for the case *b)*, have not mitigated (Table 14); the mitigation appears in other harmonic orders (Table 15). For this, to compare the harmonic degree is used the maximum-magnitude cancellation index:

$$M_h = \left(1 - \frac{I(A,B,C)_{h-TWC\,case\,b}}{I(A,B,C)_{h-TWC\,case\,a}}\, x\ 100\%\right) \quad (2)$$

This index is understood as a percentage of the harmonic reduction in the substation for the case *a)* compared with the case *b)*.

TABLE 14 THDI IN CASE *A)* AND *B)*

Transformer Windings Connection (TWC)	THDI	Transformer Windings Connection (TWC)	THDI
Dy5 *a)*	21,165%	Dy5 *b)*	10,985%
Dz0 *a)*	21,168%	Dz0 *b)*	10,988%
Dy11 *a)*	21,166%	Dy11 *b)*	10,986%
Dz10 *a)*	21,169%	Dz10 *b)*	10,989%
Dy1 *a)*	21,168%	Dy1 *b)*	10,987%
TWCc Case *a)*	33,564 %	TWCc Case *b)*	17,291 %

TABLE 15 HARMONIC MAXIMUM-MAGNITUDE CANCELLATION WITH TWCC FOR THE PHASE A B C

h	Case *a)*	Case *b)*	Mh *(a,b,c)*
5	107,85	36,091	66,54%
7	55,293	42,984	22,26%
11	17,454	9,9416	43,04%
13	15,092	23,019	-52,52%
17	11,642	12,909	-10,88%
19	9,9017	6,2953	36,42%
23	4,1189	9,0374	-119,41%
25	5,4414	4,8014	11,76%
29	3,6757	1,3212	64,06%
31	5,2315	5,77	-10,29%
THDI	33,56%	17,29%	48,48%

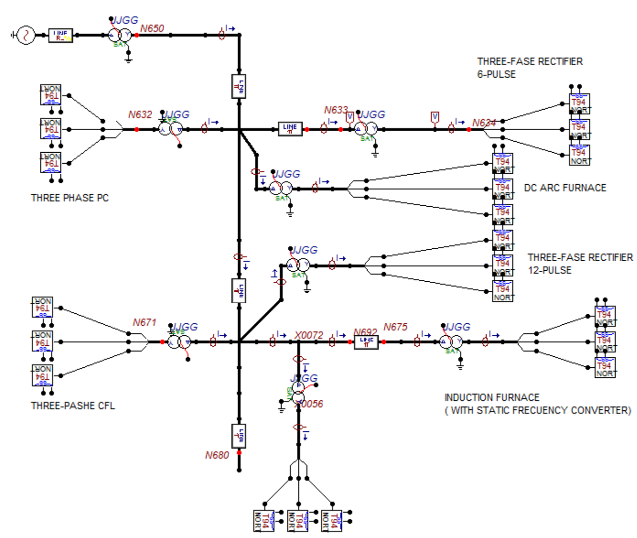

FIGURE 10. IEEE 13 NODE TEST FEEDER (MODEL ATP-EMTP)

VII. CONCLUSIONS

The paper has studied the harmonic mitigation in electrical distribution systems using Special Connections Transformers SCTs and also the implementation of standard connections that may have the same or better results on the harmonics mitigation.

Simulation results concluded that the best performance in the harmonic mitigation is presents in V-V connections and

Impedance Matching, with the lowest THDI. Harmonic mitigation using phase shifting transformer or windings connections transformer may have better results when it is implemented in networks with similar loads, as well harmonic spectrum and power.

In this way, using phase shifting transformers with 30 degrees apart (Dy1, Dz0 and Dy11 connections) can be achieved a timely and efficient solution for the mitigation of the harmonic distortion on residential and commercial users, where fluorescents compact lamps, computers and the other similar loads are predominant in this distribution systems.

Finally, the introduction of capacitor banks for power factor correction may affect the harmonic distortion, mainly due to the response of the capacitor bank as a harmonic multiplier source when it subjected to operate under such conditions.

VIII. ACKNOWLEDGEMENTS

The authors thank the Universidad Industrial de Santander for their support of this research through the project DIEF VIE-5566.

IX. REFERENCES

[1] D. Matvoz and M. Maksić, "Impact of compact fluorescent lamps on the electric power network," in *International Conference on Harmonics and Quality of Power*, Wollongong, NSW, 2008.

[2] M. Al-Dabbagh, A. Muhammad, R. H. Khawaja, M. Akmal and M. R. Arif, "Impact of compact fluorescent lamp on power quality," in *Power Engineering Conference AUPEC '08 Australasian Universities*, Sydney, NSW, 2008.

[3] D. Chapman, "Harmonics: Causes and Effects," *Power Quality Application Guide*, 2001.

[4] D. D. Shipp and W. S. Vilcheck, "Power quality and line considerations for variable speed AC drives," *IEEE Transactions on Industry Applications*, vol. 32, no. 2, pp. 403-410, 1996.

[5] J. Suarez, G. F. D. Mauro, D. Anaut and C. Agüero, "Analysis of the Harmonic Distortion and the Effects of Attenuation and Diversity in Residential Areas," *IEEE Latin America Transactions*, vol. 3, no. 5, pp. 53-59, 2005.

[6] R. Singh and A. Singh, "Aging of Distribution Transformers due to Harmonics," in *IEEE International Conference on Condition Monitoring and Diagnosis*, Bali, Indonesia, 2012.

[7] E. E. Ahmed, M. Abdel-Aziz, E. A. El-Zahab and W. Xu, "Investigation and mitigation of harmonics from electric arc furnaces," in *Canadian Conference on electrical and Computer Engineering*, Edmonton, Alberta, Canada, 1999.

[8] M. Izhar, C. M. Hadzer, M. Syafrudin, S. B. Taib and S. Idris, "Performance for Passive and Active Power Filter in Reducing Harmonics in the Distribution System," in *National Power & Energy Conference (PECon) 2004 Proceedings.*, Malaysia , 2004.

[9] K. Wada and T. Shimizu, "Mitigation method of 3rd-harmonic voltage for a three-phase four-wire distribution system based on a series active filter for the neutral conductor," in *Department of Electrical Engineering*, Tokyo, 2002.

[10] A. Baggini, "Harmonics: Neutral sizing in harmonic rich installations," *Power Quality Application Guide*, vol. 3.5.1, pp. 1-7, 2003.

[11] D. M. Said and K. B. M. Nor, "Effects of harmonics on distribution transformers," in *Power Engineering Conference, AUPEC '08. Australasian Universities*, Sydney, NSW, 2008.

[12] M. Shareghi, B. Phung, M. Naderi, T. Blackburn and E. Ambikairajah, "Effects of current and voltage harmonics on distribution transformer losses," in *International Conference on Condition Monitoring and Diagnosis (CMD)*, Bali, 2012.

[13] J.-G. Boudrias, "Harmonic mitigation, power factor correction and energy Saving with proper transformer and phase shifting Techniques," in *Conference on Electrical and Computer Engineering.*, Canadian, 2004.

[14] A. Baggini and Z. Hanzelka, "Voltage and Current Harmonics," in *Handbook of Power Quality*, John Wiley & Sons, 2008, pp. 228-229.

[15] H. d. Keulenaer, "Introduction: Power Quality Self-assessment Guide," *Power Quality Application Guide*, vol. 1.2, pp. 3-7, 2002.

[16] P.-M. Nicolae, "The Impact of Currents Harmonics over the Voltage," in *Symposium on Industrial Electronics (ISIE)*, Gdansk, 2011.

[17] IEEE Std 519, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, Institute of Electrical and Electronics Engineers, 1992.

[18] IEC 61000-3-2, Electromagnetic compatibility (EMC) - Part 3-2 - Limits - Limits for harmonic current emissions (equipment input current ≤ 16 A per phase), International Electrotechnical Commission, 2005.

[19] IEC 61000-3-4, Electromagnetic compatibility (EMC) - Part 3-4: Limits - Limitation of emission of harmonic currents in low-voltage power supply systems for equipment with rated current greater than 16 A, International Electrotechnical Commission, 1998.

[20] H. Funato, C. Sasaki, Y. Chiku and S. Ogasawara, "Analysis of Loss of Receiving Transformer Caused by Harmonic Current and Voltage for Loss Reduction," in *14th International Power Electronics and Motion Control Conference, EPE-PEMC*, 2010.

[21] IEEE Std C57.110, IEEE Recommended Practice for Establishing Liquid-Filled and Dry- Type Power and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents, Institute of Electrical and Electronics Engineers, 2008.

[22] IEC 61378-1, Converter transformers – Part 1: Transformers for industrial applications, International Electrotechnical Commission, 2011.

[23] IEEE Std C57.17, IEEE Standard Requirements for Arc Furnace Transformers, Institute of Electrical and Electronics Engineers, 2012.

[24] UL 1561, Dry-Type General Purpose and Power Transformers, Underwriters Laboratories, 2011.

[25] UL 1562, Transformers, Distribution, Dry-Type-Over 600 Volts, Underwriters Laboratories, 2013.

[26] J. Desmet and G. Delaere, "Harmonics: Selection and Rating of Transformers," *Hogeschool West-Vlaanderen & Gregory Delaere*, vol. 3.5.2, pp. 3-4, 2005.

[27] NEMA MG 1, Motors and Generators, National Electrical Manufacturers Association, 2011.

[28] IEC 60034-26, Rotating electrical machines –Part 26: Effects of unbalanced voltages on the performance of three-phase cage induction motors, International Electrotechnical Commission,

2006.

[29] IEC TR 61000-5-6, Electromagnetic compatibility (EMC) –Part 5-6: Installation and mitigation guidelines – Mitigation of external EM influences., International Electrotechnical Commision, 2002.

[30] W. Langguth, Basic Principles of Physics for Electromagnetic Compatibility (EMC) and their Application to Electrical Installations in Buildings, University of Applied Sciences, 2004.

[31] B.-S. G. Bin-Kwie Chen, "Three phase models of specially connected transformers," *IEEE Transactions on Power Delivery,* vol. 11, pp. 323-330, 1996.

[32] H. Roussel, "Power supply for the Atlantic TGV high speed line," in *International Conference on Main Line Railway Electrification*, York, 1989.

[33] E. Tiippana, "Supply of electricity for electrified lines in Finland," in *International Conference on Main Line Railway Electrification*, York, 1989.

[34] L. Qun-Zhan, Z. Jin-Si and Q. Qing-Quan, "Browse Conference Publications > Main Line Railway Electrifica ... Help Back to Results | Next »," in *International Conference on Main Line Railway Electrification*, York, 1989.

[35] S. Case, A. Hayes, J. McNeil, R. Morrison and E. Riches, "Electrification of Taiwan main-line railway from Keelung to Kaohsiung," *IEE Proceedings B Electric Power Applications,* vol. 130 , no. 5, pp. 289-301, 1983.

[36] Task Force on harmonics Modeling and Simulations, IEEE PES Harmonic Working Group, "Characteristics and Modeling of harmonic sources- Power Electronics Devices," *IEEE Transactions on Power Delivery,* vol. 16, pp. 791-800, 2001.