Harmonics Based Clustering Patterns Featured by the Final Nodes of a WPT tree

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***Abstract* - Decompositions of electric waveforms relying on the Wavelet Package Transform (WPT) provide numerous advantages but require a significant amount of computational resources (runtime and memory). A tree topology with 7 levels, relying on a wavelet mother from Daubechies family with a filter of 28 components was studied. Studies on artificial waveforms polluted with a single harmonic were made firstly, revealing interesting aspects relative to clusters of nodes affected by the same group of harmonic orders. Different pairing patterns of odd and even harmonics were revealed, along with decisions on nodes being more relevant for certain harmonics. Nodes clustering patterns with respect to the most significant odd harmonic orders were deduced as well. These patterns consist in sequences of 4, 8 and 32 nodes. Similarities in harmonic weights associated to node clustering patterns based on the most significant harmonic orders were also derived and discussed. The harmonics-nodes clustering properties were afterward tested with respect to capabilities related to time-frequency identification of most common harmonic orders magnitudes modification. Multi-harmonic artificial test signals, similar to those from power applications were used to validate the original WPT based algorithms relying on the special clustering and patterns-related properties derived by authors. The results were commented and conclusions were drawn.**

Cuvinte cheie: *analiza sistemelor de putere, calitatea puterii, arbori de tip WPT, analiza asistata de calculator.*

Keywords: *power system analysis, power quality, WPT trees, computer aided analysis.*

I. INTRODUCTION

Identification of harmonic related disturbances has been representing a permanent concern for professionals all over the world, a common approach being the utilization of wavelet-based techniques [1].

For example, using wavelets, Chan, W.L., a.o. [1] proved that each type of current waveform polluted with power harmonics can be represented well by a normalized energy vector. Such vectors can be used for harmonics signature recognition, the corresponding system performing well in tandem with an artificial neural network (NN).

Similarly, a comparative study was made by Srivastava, Gupta a.o. [2], relative to neural NN-s related training algorithms. The studied NN was trained to extract important features from the input current waveform to uniquely identify various types of devices using their distinct harmonic signatures. The particle swarm optimization (PSO), genetic algorithm, gradient descent (GD), and respectively a hybrid of PSO&GD were analyzed, the last one proving to be superior.

Remarkable results obtained with a wavelet-genetic algorithm-neural network-based hybrid model relative to accurate prediction of short-term load forecast were communicated by Lai and Zhou [3].

Interesting wavelet-based algorithms for the harmonic analysis in power systems were also proposed in [4]-[7].

Some of the people authoring this paper started to study intensively the advantages provided by the analysis based on the Wavelet Package Transform (WPT) [8], a special attention being paid to computational techniques required to optimize the WPT algorithms in order to reduce as much as possible the required resources [9],[10]. New data acquisition systems (DAS) described in [11], were available now for the research team. They have been used to record and evaluate power quality indices for electrical waveforms acquired from test points established by the industrial partners. These DAS provide much better sampling rates (700 samples per period). Therefore a new WPT trees topology, with 7 levels, had to be studied, such as to take fool advantage on the better sampling rate [10]. As more nodes in the tree involve not only more information on higher harmonic ranks but also more computational resources, this study is also concerned with special techniques to reduce these costs.

II. NODES-HARMONICS PAIRING PATTERNS

Original programs were conceived for the study of [8],[10] „nodes-harmonics" pairing patterns exhibited by harmonics when using a 7 levels WPT tree with a wavelet mother db14 (Daubechies family, filter with 28 components). The analyzed signals were obtained as sum between a perfect sine waveform and a single harmonic whose order varies from 2 to 256.

In a 1-st approach it was derived that the vectors hosted by the nodes from the 7-th level (terminal nodes) are affected only by certain harmonics. Fig. 1 presents the number of harmonic orders which affect each node such as to transmit more than 1% from its energy in it.

Fig. 1 reveals a non-uniform distribution of harmonic energies in the terminal nodes. Whilst certain nodes are affected by a small number of harmonic orders (at least 3),

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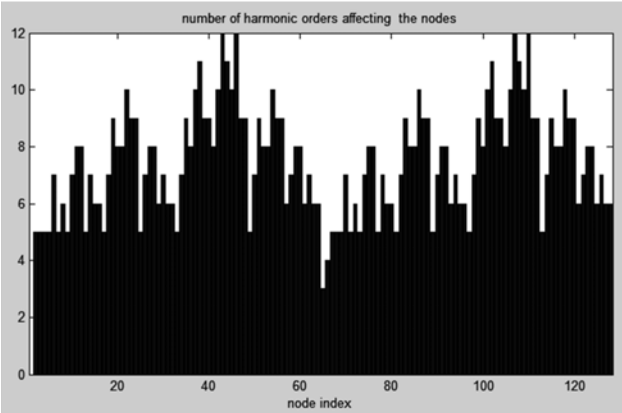

Fig. 1. Number of harmonic orders affecting the nodes

others can be affected by as much as 12 harmonic orders.

It was observed that the energy weights related to odd harmonics were phase-invariant (very small variations are highlighted for orders smaller than 9). On the other hand, the harmonic weights related to even harmonics were found to vary strongly with the phase shift. No systematic rule for their variation with the phase shift could be deduced at a first glance. Fig. 2 represents the energy weights per node related to even harmonics (for the harmonic orders from 2 to 128), for a particular phase-shift. Fig. 3 is the counterpart of Fig. 2, now for odd harmonics. The maxim possible harmonic weights with respect to phase shifts were considered. Both figures demonstrate a certain grouping of energy weights (restricted groups of harmonic orders tend to influence the same restricted group of nodes).

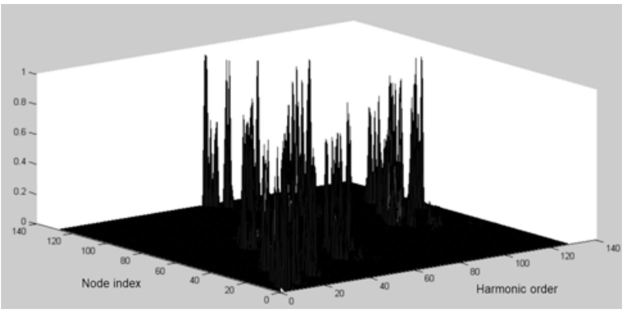

Fig. 2. Energy weights per node provided by even harmonics.

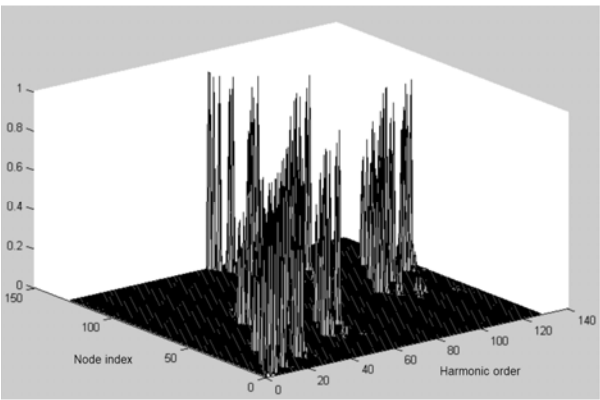

Fig. 3. Energy weights per node related to odd harmonics

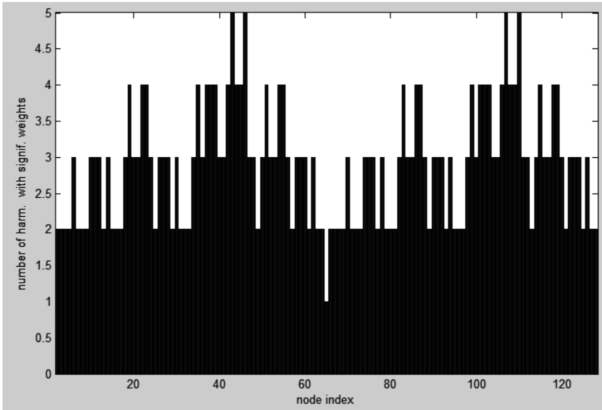

Fig. 4. Number of odd harmonic orders with more than 1% from their energy affecting the node.

A. Pairing patterns of odd harmonics

Fig. 4 was generated to represent the number of odd harmonic orders that significantly affect the nodes. Many nodes are affected only by 2 odd harmonics. 44 of them are involved in 22 pairs of nodes according to the pattern "both nodes in the pair are affected only by 2 odd harmonics, in a complementarily mode, and these 2 harmonics affect only the nodes from the respective pair".

Other 2 types of “clustering” patterns were revealed as well. They can be described as „clusters of *x* nodes, affected only by at most *x* odd harmonic orders belonging to the same set”, where *x* can be either 4 or 8.

Actually all nodes are involved in one of the clusters mentioned above, the whole range of odd harmonics from 3 to 255 being involved in the clustering mechanism, as revealed by Fig. 5. An important notice must be done: even if involved in clusters of 4 or of 8 nodes, the odd harmonic orders are still paired on a „2 – basis” considering the node associated to their most significant weight, which is higher than 0.5 (node denoted by MSN). The MSN is paired for the same couple of harmonics with a node where one can find a neighboring odd harmonic order (e.g. in Table I, the harmonic order 115 affects the MSN node 38 and make a pair with the neighboring odd harmonic order 117 whose MSN node is 40). In this table the MSN nodes are represented with bold fonts.

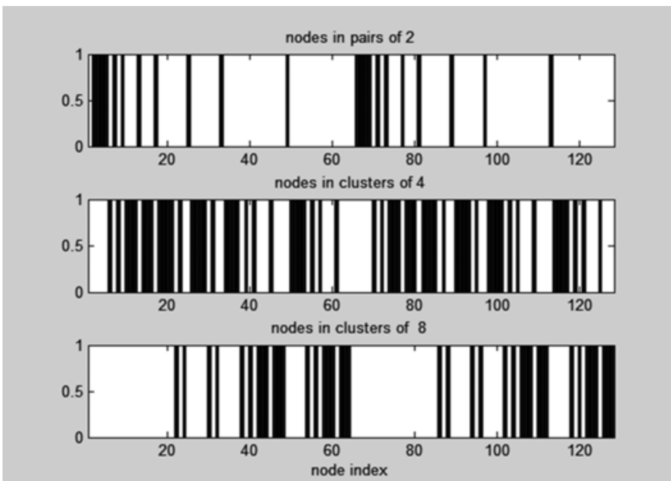

Fig. 5. Distribution of odd harmonic orders considering the clustering patterns.

TABLE I.
EXAMPLE FOR A CLUSTER WITH 8 NODES (WEIGHTS ROUNDED TO 2 DIGITS FOR THE FRACTIONAL PART) – ODD HARMONICS

Node index	Harmonic order							
	107	*109*	*115*	*117*	*139*	*141*	*147*	*149*
38		0.05	**0.74**	0.01		0.19		
40			0.01	**0.74**	0.2			
46		**0.82**	0.05					
48	**0.89**	0.02						0.08
102			0.19		0.01	**0.74**	0.05	
104				0.23	**0.74**	0.01		
110		0.10	0.01			0.05	**0.82**	0.02
112	0.08						0.02	**0.89**

B. *Pairing patterns of even harmonics*

The weights of even harmonic orders are highly variable with the phase shift. Fig. 6 represents the number of even harmonic orders which influence the same node such as to transmit to it more than 1% from its energy.

There is no „singular" node from the even harmonic orders point of view. To be more specific, there aren't any nodes influenced by a single even harmonic (at least 2 even harmonic orders affect a node).Moreover, most of the nodes are affected by at least 3 even harmonics (except for the nodes 65 and 66, which are affected by only 2 even harmonic orders).

On the other side, the maximum number of even harmonics which can affect a node is 7. 8 nodes are in this situation.

There aren't any exclusive pairings of even harmonics, similar to that exhibited by the odd harmonics. But there is an interesting property, namely the complementarity relative to the identical ranges of variation of the harmonic weights associated to an even harmonic order. The even harmonic orders influence only pairs of nodes. The number of node pairs influenced by an even harmonic order varies from 1 to 4. Certain examples for each of these cases are provided by Table II, where the ranges for harmonic energy weights variation are mentioned as well.

Fig. 7 reveals the assignment of nodes to clusters on a "single even harmonic order influence" basis.

C. *Conclusions on pairing patterns*

The analysis of all results related to odd harmonics (denoted by OH) yielded the following conclusions:

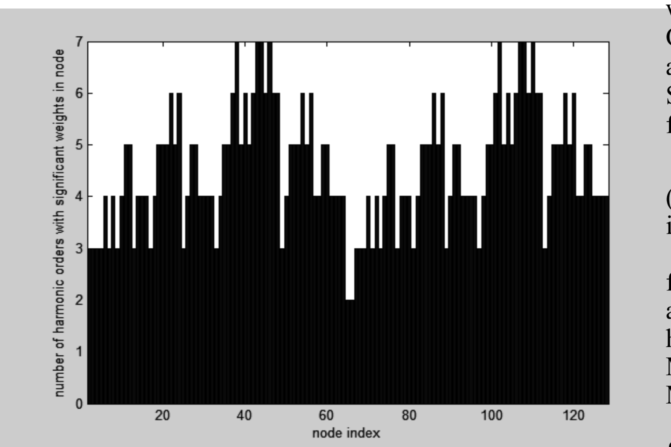

Fig. 6. Number of even harmonic orders with significant weights in nodes.

TABLE II.
EXAMPLES OF DIFFERENT NUMBERS OF PAIRS OF NODES AFFECTED BY A SINGLE EVEN HARMONIC ORDER

One pair of affected nodes	2 pairs of affected nodes	3 pairs of affected nodes	4 pairs of affected nodes
harm.no.4	**harm.no.6**	**harm.no.26**	**harm.no.142**
node no.2 range [0.038 , 0.962] node no.4 range [0.038 , 0.962]	node no.3 range [0.035 , 0.946] node no.4 range [0.035 , 0.946] node no.7 range [0.001 , 0.018] node no.8 range [0.001 , 0.018]	node no.11 range [0.007 , 0.915] node no.12 range [0.007 , 0.915] node no.15 range [0.001 , 0.017] node no.16 range [0.001 , 0.017] node no.27 range [0.002 , 0.057] node no.28 range [0.002 , 0.057]	node no.37 range [0.000 , 0.155] node no.38 range [0.000 , 0.155] node no.45 range [0.001 , 0.026] node no.46 range [0.001 , 0.026] node no.101 range [0.001 , 0.693] node no.102 range [0.001 , 0.693] node no.109 range [0.007 , 0.116] node no.110 range [0.007 , 0.116]

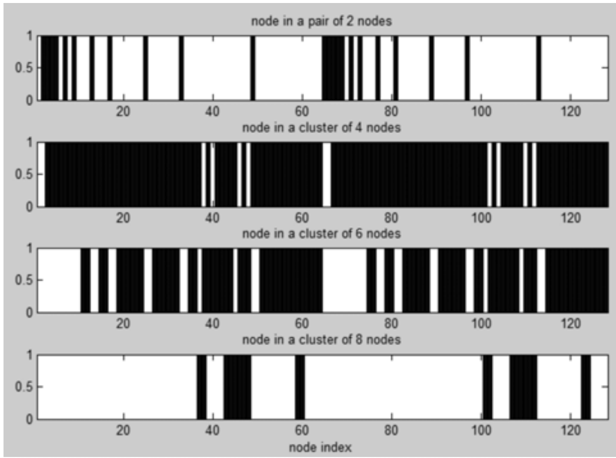

Fig. 7. Assignment of nodes to clusters on an "even harmonic order influence" basis.

- There is at most one MSN per OH. Up to the 57-th OH, for each OH there is at most one node other than MSN (referred from this point on as "secondary node" and denoted by SN) whose weight is higher than 0.05;
- 16 OH-s belonging to the set {57,71,109,111,113,119, 121,135,137,145,147,151,183,185,199,201} , are associated to 2 SN nodes exhibiting weights greater than 0.05, whilst for the 143-rd harmonic there are 3. Except for the OH-s 57 and 71 (which in practical applications are usually almost 0), all the remaining OH-s with more than one SN are usually from the electromagnetic noise range of frequencies!

The analysis of all results related to even harmonics (denoted from this point on by EH) resulted in the following conclusions:

- For each EH, irrespective to the number of nodes influenced by it, there is a single pair of nodes for which the associated EH's weight range of variation has a maximum higher than 0.5. This maximum weight will be denoted by MPW and the associated pair of nodes will be denoted by MSP;
- When a MSP has a MPW>0.95 , the rest of nodes affected by the corresponding EH will be neglected. Otherwise (if MPW<0.95), a second pair of nodes (denoted

Fig. 8. Harmonic orders versus indices of nodes (for odd harmonics) or pairs of nodes (for even harmonics) carrying most of their weights.

from this point on by SP) can present interest, namely the one affected by a maximum weight higher than 0.05;

- Usually an EH is associated to at most one SP. 4 cases disobey this rule, namely those associated to the harmonic orders from the set {110, 114, 142 and 146}, but as long as all of them belong to the range of frequencies associated to electromagnetic noise this should not be a real concern.

III. HARMONICS BASED CLUSTERING PATTERNS OF TERMINAL NODES

A. Per-node triplets of most significant harmonic orders

Fig. 8 was built by using the *MSN*s and respectively the nodes from each *MSP* based on the conclusions of the previous section. The harmonic orders represented on the OY axis will be referred from this point on as „most significant" [10].

This study revealed that:

- Each node *N* is associated to exactly 3 „most significant" harmonic orders, found in a sequence of consecutive numbers, two of them being even (e.g. the 3-rd node is affected by the „most significant" harmonic orders 6, 7 and 8);
- Each of the even significant harmonic orders (*H*) affecting *N* is also appearing in the other node which is part of the „most significant pair" associated to *H* (e.g the 8-th harmonic order appears both in the 3-rd and the 7-th nodes, which are connected in its MSP).

B. Nodes clustering patterns with respect to the most significant odd harmonic orders

Further original computer-based studies revealed the existence of certain clustering patterns with respect to the most significant odd harmonic orders affecting sequences of consecutive terminal nodes.

In the first place, there are 2 elementary patterns (sequences of 4 consecutive nodes) which can be defined based on the most significant odd harmonic orders (MSOH).

Let us denote by *x* and *y* the most significant odd harmonic orders affecting the leftmost node of the above mentioned 2 elementary patterns. Then:

- the elementary pattern of 1-st type (denoted by EP1) starts with a sequence of 3 nodes characterized by increasing MSOH-s: x,x+2,x+4,x-2;
- the elementary pattern of 2-nd type (denoted by EP2) starts with a sequence of 3 nodes characterized by decreasing MSOH-s: y,y-2,y-4,y+2.

The 2-nd class of patterns consists in sequences of 8 nodes. A pattern of this type aggregates 2 different elementary patterns, following the rule y=x+14, as described below:

- the 8 elements pattern of type A (denoted by PA) actually consists of a pair of type (EP1, EP2);
- similarly, the 8 elements pattern of type B (denoted by PB) consists of a pair of type (EP2, EP1).

Finally the last type of patterns, made of 32 consecutive nodes, is built on 4 patterns of type A and B. The 1-st type of longest pattern (called P_ABBA) comes from the aggregation of 4 patterns of 8 elements, according to the sequence PA, PB, PB, PA. On the other hand, the 2-nd type of longest pattern (denoted by P_BAAB) involves the sequence PB, PA, PA, PB.

Table III gathers the differences between the MSOH characterizing the neighboring edge nodes of PA/PB patterns from a pattern of 32 consecutive nodes. These differences are computed as *i1*-*i2*, where *i1* represents the MSOH of the rightmost node of the PA/PB pattern placed in the *x*-th position whilst *i2* represents the MSOH of the leftmost node of the PA/PB pattern from the (*x*+1)-th place belonging to the same pattern of 32 consecutive nodes. As expected, due to the symmetry of the WPT tree,

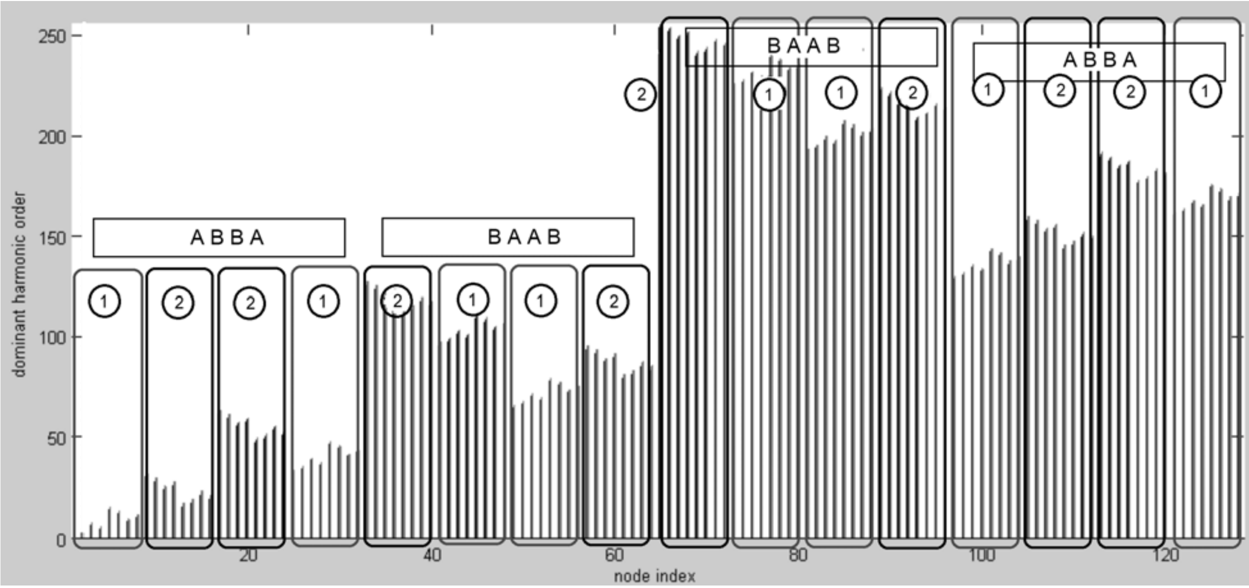

Fig. 9. Terminal nodes clustering with respect to the most significant harmonic order.

TABLE III.
DIFFERENCES BETWEEN THE MOST SIGNIFICANT ODD HARMONIC ORDERS CHARACTERIZING TRANSITIONS BETWEEN 8 NODES PATTERNS

Pattern type	Transition		
	1-st	2-nd	3-rd
P_ABBA	20	42	-20
P_BAAB	-20	-42	20

the differences characterizing the transitions are also symmetric relative to 0. Fig. 9 presents the overall picture of the terminal nodes clustering with respect to MSOH. The patterns of EP1 type are marked by "1" whilst the patterns of EP2 type are marked by "2".

C. Similarities in harmonic weights associated to node clustering patterns based on the most significant harmonic orders

Fig. 10 depicts the highest harmonic weights associated to A/B node clustering patterns based on the most significant harmonic orders. They will be indexed in a left-right, top-bottom manner. Partial, total or "scaled" similarities could be noticed, as follows:

(a) Two classes of "weight based" patterns were identified, one per each pattern of type A and B respectively;

(b) In the first class (associated to A patterns), the "reference" harmonic weight distribution could be noticed in the clusters with indices 4, 10 (with insignificantly small deviations) and 16. Very similar harmonic weight distributions (up to a scale factor smaller but close to 1) are exhibited by the clusters with indices 6, 7 and 11, whilst the 13-th cluster is characterized by a smaller scale factor. The 1-st cluster (which includes the 1-st terminal node, hosting only the energy for the fundamental frequency) has identical weights for its final 4 nodes, but higher values for the first ones;

(c) In the 2-nd class (associated to B patterns), the "reference" harmonic weight distribution could be noticed in the clusters with indices 2, 8 and 16. Very similar harmonic weight distributions (up to a scale factor smaller but close to 1) are exhibited by the clusters with indices 3, 14 and 15, whilst the 5-th cluster is characterized by a smaller scale factor. The 9-th cluster (which is symmetrical rela-

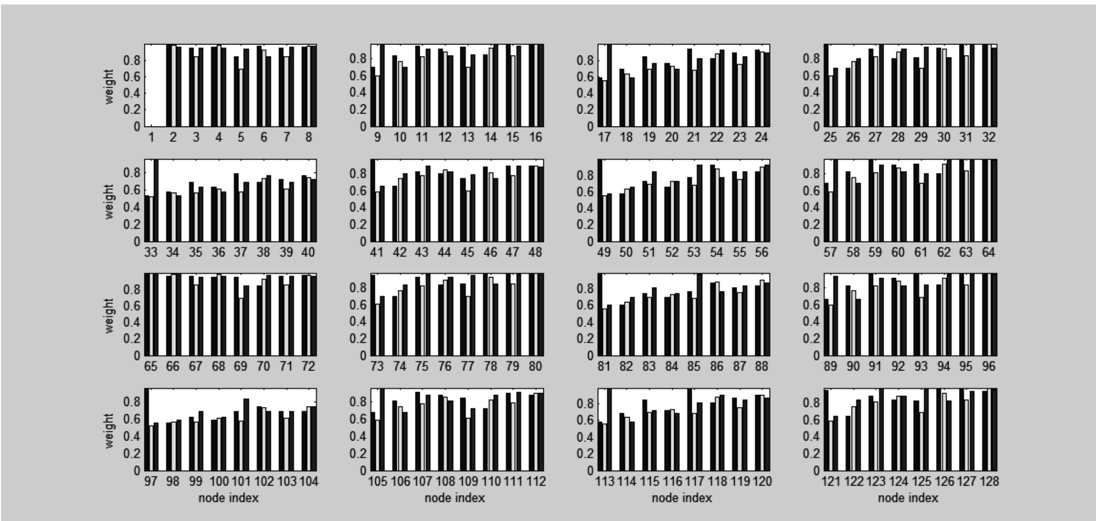

Fig. 10. Highest harmonic weights associated to node clustering patterns based on the most significant harmonic orders.

tive to the 1-st one, if considering the total number of 8 nodes clusters as being equal to 16!) has the identical weights for its final 4 nodes, but higher values for the first ones.

IV. TESTING THE (HARMONICS – NODES) CLUSTERING PROPERTIES

A. *Tests setup*

The association between nodes and “most significant” harmonics along with the harmonics – nodes clustering patterns makes possible a more accurate localization of the frequency range responsible for a fault whilst preserving the time-related information. This is possible because the energy of nodes associated to the „guilty” harmonics is modified.

In order to test the ability of the original algorithms relative to identification of harmonic spectra modification by means of terminal nodes energies, synthetic signals similar to those from power applications were used. A test signal was obtained by using the superposition theorem to pollute a perfect sinusoid with harmonics up to the 27-th order. As long as the signal magnitude does not affect the WPT clustering properties, the fundamental magnitude was set to 30, the phase shifts were randomized and the harmonic weights were set according to Table IV. An example of 1-st period from a test signal is depicted by Fig. 11.

A test signal consisted in two periods. In the 2-nd period, each of the harmonic orders from the set S={2,3,5,7,9,11,13,15,17} , in distinct test signals, was doubled in the second period. The harmonic orders from S and the weights from Table IV were selected on applicability considerations.

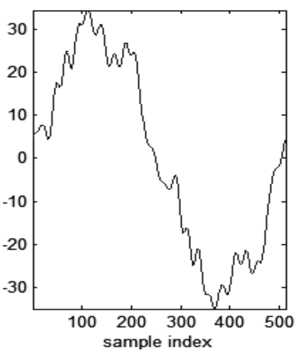

Fig. 11. Example of 1-st period from a test signal.

TABLE IV.
WEIGHTS OF HARMONICS AFFECTING THE TEST SIGNALS

Harmonic order	Weight [%]	Harmonic order	Weight [%]	Harmonic order	Weight [%]
2	1	9	0.3	19	0.05
3	2	11	5	21	5
4	0.1	13	3	23	3
5	13	15	2	25	2
7	7	17	1	27	1

TABLE V
NODES AFFECTED BY THE TESTED HARMONICS IN A WPT TREE DECOMPOSITION OF A MONO-HARMONIC SIGNAL

Harmonic order	Node/Weight	Node/Weight	Node/Weight
2	2/1		
3	2/0.981	4/0.019	
5	2/0.019	4/0.981	
7	3/0.849	7/0.151	
9	3/0.151	7/0.849	
11	6/0.018	8/0.976	
13	6/0.922	8/0.017	14/0.059
15	5/0.696	13/0.303	
17	5/0.303	13/0.696	

Table V gathers the set of nodes (set denoted by SN) which are influenced by the harmonics from S, along with the corresponding harmonics energy weights, as yielded by the studies on mono-harmonic signals.

The set of nodes affected by the harmonics orders from S are also affected by harmonic orders other than those from S, as proved in previous sections from this paper.

Table VI gathers all harmonic orders affecting the nodes from SN, along with their weights and clustering symbols. The symbol Ex was used to represent the even harmonic order which can affects a pair of nodes. For example E1 denotes that both the 2-nd and 4-th node are affected by the 4-th harmonic. The harmonic weight varies for these nodes in a complementary way such as to be in each of them at least 0.038 and at most 0.962. „Exa/b” was used when SPs are present. The symbols “Ox(a/b)” were used to represent a pair or quadruple of odd harmonic orders which can be affected by the same pair/ quadruple of odd harmonics according to the clustering mechanism explained in Section II.A. The * was used to denote a harmonic order included in the test signal.

TABLE VI
ALL HARMONIC ORDERS AFFECTING THE NODES AFFECTED BY THE TESTED HARMONICS IN A WPT TREE DECOMPOSITION OF A MONO-HARMONIC SIGNAL

Id node	Most significant harmonics/range of weights and clustering symbols			Harmonics with smaller weights / range of weights and pairing symbols	
2	2/1*	3/0.98 (O0a) *	4/[0.038 , 0.962] (E1)	5/0.02 (O0b)*	
3	6/[0.035 , 0.946] (E2)	7/0.849 (O1a)*	8/[0.047 , 0.953] (E3)	9/0.151 (O2a) *	
4	4/[0.038 , 0.962] (E1)	5/0.98*	6/[0.035 , 0.946] (E2)	3/0.019* (O0B)	
5	14/[0.007 , 0.842] (E6a)	15/0.696 (O2a)*	16/[0.066 , 0.933] (E7)	17/0.303 (O3a)*	18/[0.004 , 0.146] (E8b)
6	12/[0.011 , 0.970] (E5)	13/0.922 (O7a)*	14/[0.007 , 0.842] (E6a)	19/0.059*	18/[0.004 , 0.146] (E8b)
7	8/[0.047 , 0.953] (E3)	9/0.849 (O2b)*	10/[0.025 , 0.956] (E4)	7/0.151 (O1b)*	
8	10/[0.025 , 0.956] (E4)	11/0.976 *	12/[0.011 , 0.970] (E5)	13/0.017 (O7b)*	
13	16/[0.066 , 0.933] (E7)	17/0.696 (O3b)*	18/[0.005 , 0.843] (E8a)	15/0.303 (O2b)*	14/[0.005 , 0.146] (E6b)

Two types of graphs (G1 and G2) were drawn for each test. Denoting by Ey_i the energy of the i-th node in the y-th period, G1 represents the differences ($E2_i$- $E1_i$) and G2 represents the relative percentage differences ($E2_i$ - $E1_i$) / $E1_i$ x 100.

B. Tests results

A representation of energies of vectors hosted by all terminal nodes from the WPT tree used to decompose all tested signal (Fig. 12) revealed a 1-st validation of the algorithm, because only the low order nodes carry significant energies, being the only ones polluted by the low harmonic orders, as those from the test signals are.

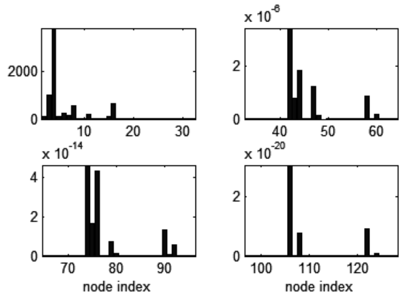

Fig. 12. Terminal nodes energies for a test signal.

Fig. 13 depicts G1 and G2 for the tests concerned with the harmonics from *S*. Table VII gathers the tests results. The "most significantly affected node in graphs" property (from mono-harmonic studies) was emphasized through bolded fonts. The symbol * was used when this property was not correctly revealed by tests.

TABLE VII.
TESTS RESULTS

Id node	Graphs with significant modification of nodes energies	
	G1	G2
2	**H2,H3,** H5	**H2,H3,** H5
3	**H7**,H9	H7*,H9
4	H3,**H5**	H3,**H5**
5	**H15,H17***	**H15**,H17
6	**H13**	**H13**
7	H7,**H9**	**H7*, H9**
8	**H11**, H13	**H11**,H13
13	H15,H17*	H15,H17

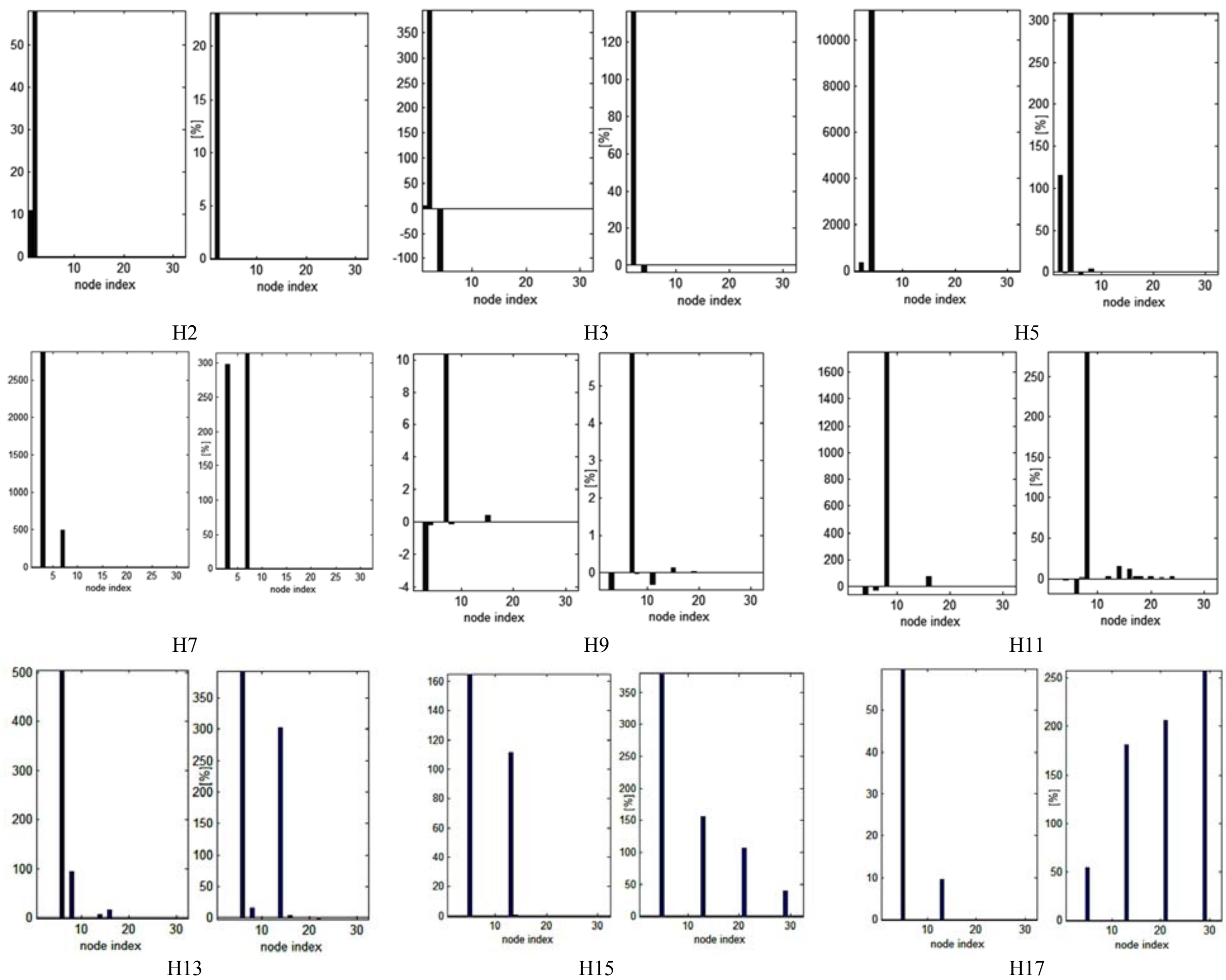

Fig. 13. Graphs G1 (left) and G2 (right) , labeled Hx, associated to the energies of terminal nodes when varying the harmonic order Hx, with x in the set {2,3,4,5,7,9,11,13,15,17}

The tests results reveal the „expected behavior" of terminal nodes energies for the nodes with indices 2,4,6 and 8. On the other hand, the 3-rd and 7-th nodes were expected to record relative percentage deviations in the reversed order for the test related to the 7-th harmonic (because the 3-rd node is MSN for it, in a pair with the 7-th node). Actually they „switched places" (actually for a small difference) only in the G2 diagram, G1 being correct for both of them. It is worth noticing that the harmonics no. 7 and 9 are „consecutive" in the list of odd harmonics.

A similar "places switching", this time in G1s, can be observed for the 5-th and 13-th nodes relative to H17, which are at their turn paired by the "neighboring" harmonics no. 15 and 17. But, as long as the correct relation is exhibited by the G2 graph, this should not be a concern.

One should also notice the presence of "negative deviations" in the graphs G1 exhibited by the less significant nodes of H3 and H9, accompanied by very small negative deviations in the corresponding G2s. This phenomenon is in correlation to the significant undulating nature of the vectors from the terminal nodes and does not affect the automated diagnosis method relying on WPT.

The G1 graphs are very useful also when fake deviations like those from G2 appear for nodes usually not affected in that harmonic context. These fake deviations are simply to remove when are not accompanied by corresponding significant deviations in the G1 graphs.

CONCLUSION

For the studied WPT tree the studies on mono-harmonic artificial signals revealed that:

a) The odd harmonics determine clusters of 2 , 4 and 8 terminal nodes affected only by sets of 2, 4 and 8 harmonic orders, accordingly. Of them, only one node has most of the harmonic weight and at most a single different node, hosting the most significant remaining weight, has to be considered. The rest can be neglected while preserving an acceptable accuracy;

b) The even harmonics determine clusters of pairs of nodes, hosting weights in a complementary way from specific ranges of values. One even harmonic can determine clusters of 1...4 pairs of nodes. Of them, only one pair hosts most of the harmonic weight and a single different pair, hosting the most significant remaining weight, has to be considered. The rest can be neglected while preserving an acceptable accuracy;

c) Each terminal node N can be associated to exactly 3 „most significant" harmonic orders, found in a sequence of consecutive numbers. Two of them are even. Each of the even significant harmonic orders (H) affecting N is also appearing in the other node which is part of the „most significant pair" associated to H ;

d) Three type of clustering patterns could be identified with respect to the most significant odd harmonic orders affecting sequences of consecutive terminal nodes. The basic ones (consisting in 4 nodes) can be grouped in patterns of 8 nodes which finally contribute to the assembling of patterns made of 32 nodes;

e) Two classes of "weight based" patterns were identified, one per each pattern consisting of 32 nodes.

The association between nodes and "most significant" harmonics along with harmonics – nodes clustering patterns makes possible a more accurate localization of the frequency range responsible for a fault while preserving the time-related information. This is possible because the energy of nodes associated to the „guilty" harmonics is modified.

The percentage relative differences between the energies of terminal nodes proved to be a reliable criterion for this aim. Sometimes they must be used jointly with the absolute differences between energies and nodes, mainly when the deviating harmonic is an odd harmonic involved in a pair with another one.

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