Modeling and control of 41-level inverter using best switching angles calculation method

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Article Info	ABSTRACT

In this paper, analysis and modeling of a single-phase H-bridge forty-one level inverter are considered. The control of proposed inverter by equal-phase and half-height methods is implemented. MATLAB/Simulink environments are used to simulate the model and show obtained results of waveforms with FFT analysis. Eventually, the total harmonic distortion obtained for each level with the two methods is presented, comparatively, for a comparison.

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1. INTRODUCTION

Uses of cascaded H-bridge inverter have become more popular in power electronic applications because the simplicity of control and the ability to generate high output voltage levels [1, 2]. Inverters can be classified into two types, voltage source inverter (VSI) and current source inverter (CSI). If the DC voltage is maintained and constant, the inverter is called VSI or voltage fed inverter (VFI), else if the input current is maintained and constant, the inverter is called CSI or current fed inverter (CFI) [3-6].

In applied power engineering fields, the multilevel inverter used in many applications [7-9], there are three conventional categories of the multilevel inverters: cascaded H-bridge, neutral point clamped and flying capacitor multilevel inverter [10-12]. The multilevel inverter used for Induction heating, Traction systems, Active filtering, Motor drives, High-voltage and Medium-voltage applications [13-14]. The problem is the choice of the switching angles required to control a multi-level inverter with a minimum THD in the system, total harmonic distortion is to the ratio between the RMS value of the signal harmonics (voltage or current) and the RMS value of the fundamental frequency [15].

To overcome the mentioned problem a modeling and simulation of a 41-level inverter using the best switching angles calculation method have been proposed using Simulink/MATLAB program, this solution for multilevel inverter control based on trigonometric calculation method. This paper is organized as follows, in Section II modeling and control of a multilevel inverter using Simulink/MATLAB have been discussed with an analysis of the two control methods, equal-phase (EP) method, half-height (HH) method. The results are presented and compared in Section III. Finally, some conclusions are presented in Section IV.

2. MODELING AND CONTROL OF MULTILEVEL INVERTER

2.1. The model of multilevel inverter

The simulation model of a 41-level inverter is shown in Figure 1, consists of cascaded H-bridge inverters, DC power supplies and control block with adjusting the frequency and switching angles.
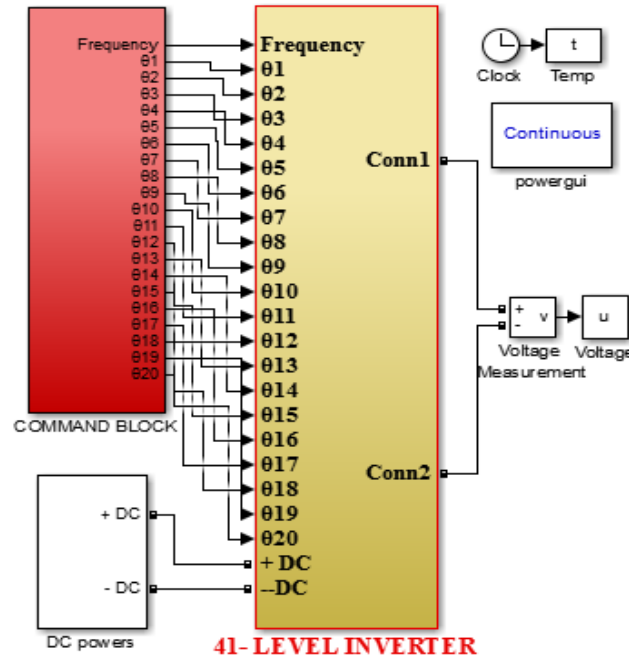

Figure 1. The MATLAB/Simulink model of 41-level inverter

2.2. Control of inverter with equal-phase method

Switching angles with the equal-phase (EP) method in degrees is shown in Table 1. The principle of this method is the division of the period (180°) by the inverter levels (m) and multiplicative the result by the number of the angle (i) [5]. The formula of calculation is given by:

$$\theta_i = \frac{180°}{m} i, \qquad i = 1,2,3,4,\dots,\frac{m-1}{2}$$

Table 1. Switching angles with the EP method in degrees

Level	Angles switching with the EP method in degrees
3	θ1= 60
5	θ1= 36; θ2= 72
7	θ1= 25.7143; θ2= 51.4286 ; θ3= 77.1429
9	θ1= 20; θ2= 40; θ3= 60; θ4= 80
11	θ1= 16.3636; θ2= 32.7273; θ3= 49.0909 ; θ4= 65.4545;θ5= 81.8182
13	θ1= 13.8462; θ2= 27.6923; θ3= 41.5385; θ4= 55.3846; θ5= 69.2308; θ6=83.0769
15	θ1= 12 ; θ2= 24; θ3= 36; θ4=48; θ5= 60; θ6= 72; θ7=84
17	θ1= 10.5882; θ2= 21.1765; θ3= 31.7647; θ4= 42.3529; θ5= 52.9412; θ6=63.5294; θ7= 74.1176; θ8= 84.7059
19	θ1= 9.4737; θ2= 18.9474; θ3= 28.4211; θ4= 37.8947; θ5=47.3684 ; θ6= 56.8421; θ7=66.3158; θ8= 75.7895; θ9= 85.2632
21	θ1= 8.5714; θ2= 17.1429; θ3= 25.7143; θ4= 34.2857; θ5= 42.8571; θ6= 51.4286; θ7= 60.0000; θ8= 68.5714; θ9= 77.1429; θ10= 85.7143
23	θ1= 7.8261; θ2= 15.6522; θ3= 23.4783; θ4= 31.3043; θ5= 39.1304; θ6= 46.9565; θ7= 54.7826; θ8= 62.6087; θ9= 70.4348; θ10= 78.2609; θ11= 86.0870
25	θ1= 7.2000; θ2= 14.4000; θ3= 21.6000; θ4= 28.8000; θ5= 36.0000; θ6= 43.2000; θ7= 50.4000; θ8= 57.6000; θ9= 64.8000; θ10= 72.0000; θ11= 79.2000; θ12=86.4000
27	θ1= 6.6667; θ2= 13.3333; θ3= 20.0000; θ4= 26.6667; θ5= 33.3333; θ6= 40.0000; θ7= 46.6667; θ8= 53.3333; θ9= 60.0000; θ10= 66.6667; θ11= 73.3333; θ12=80.0000; θ13= 86.6667
29	θ1= 6.2069; θ2= 12.4138; θ3= 18.6207; θ4= 24.8276; θ5= 31.0345; θ6= 37.2414; θ7= 43.4483; θ8= 49.6552; θ9= 55.8621; θ10= 62.0690; θ11= 68.2759; θ12=74.4828; θ13= 80.6897; θ14= 86.8966
31	θ1= 5.8065; θ2= 11.6129; θ3= 17.4194; θ4= 23.2258; θ5= 29.0323; θ6= 34.8387; θ7= 40.6452; θ8= 46.4516; θ9= 52.2581; θ10= 58.0645; θ11= 63.8710; θ12=69.6774; θ13= 75.4839; θ14= 81.2903; θ15= 87.0968

Table 1. Switching angles with the EP method in degrees (*cont*)

Level	Angles switching with the EP method in degrees
33	θ1= 5.4545; θ2= 10.9091; θ3= 16.3636; θ4= 21.8182; θ5= 27.2727; θ6= 32.7273; θ7= 38.1818; θ8= 43.6364; θ9= 49.0909; θ10= 54.5455; θ11= 60.0000; θ12=65.4545; θ13= 70.9091; θ14= 76.3636; θ15= 81.8182; θ16= 87.2727
35	θ1= 5.1429; θ2= 10.2857; θ3= 15.4286; θ4= 20.5714; θ5= 25.7143; θ6= 30.8571; θ7= 36.0000; θ8= 41.1429; θ9= 46.2857; θ10= 51.4286; θ11= 56.5714; θ12=61.7143; θ13= 66.8571; θ14= 72.0000; θ15= 77.1429; θ16= 82.2857; θ17=87.4286
37	θ1= 4.8649; θ2= 9.7297; θ3= 14.5946; θ4= 19.4595; θ5= 24.3243; θ6= 29.1892; θ7= 34.0541; θ8= 38.9189; θ9= 43.7838; θ10= 48.6486; θ11= 53.5135; θ12=58.3784; θ13= 63.2432; θ14= 68.1081; θ15= 72.9730; θ16= 77.8378; θ17=82.7027; θ18= 87.5676
39	θ1= 4.6154; θ2= 9.2308; θ3= 13.8462; θ4= 18.4615; θ5= 23.0769; θ6= 27.6923; θ7= 32.3077; θ8= 36.9231; θ9= 41.5385; θ10= 46.1538; θ11= 50.7692; θ12=55.3846; θ13= 60.0000; θ14= 64.6154; θ15= 69.2308; θ16= 73.8462; θ17=78.4615; θ18= 83.0769; θ19= 87.6923
41	θ1= 4.3902; θ2=8.7805; θ3=13.1707; θ4=17.5610; θ5=21.9512; θ6=26.3415; θ7=30.7317; θ8=35.1220; θ9= 39.5122; θ10=43.9024; θ11=48.2927; θ12=52.6829; θ13=57.0732; θ14=61.4634; θ15=65.8537; θ16=70.2439; θ17=74.6341; θ18=79.0244; θ19=83.4146; θ20=87.8049

2.3. Control of inverter with half-height method

Switching angles with the half-height (HH) is shown in Table 2. The Principe of the HH method [5] is presented by the following formula of calculation:

$$\theta_i = \sin^{-1}\left(\frac{2}{m-1}\left(i - \frac{1}{2}\right)\right) = \sin^{-1}\left(\frac{2i-1}{m-1}\right),$$

$$with \quad i = 1,2,3,4,\dots,\frac{m-1}{2}$$

Table 2. Switching angles with the HH method in degrees

Level	Angles switching with HH method in degrees
3	θ1= 30
5	θ1= 14.4775; θ2= 48.5904
7	θ1= 9.5941; θ2=30 ; θ3= 56.4427
9	θ1= 7.1808; θ2= 22.0243; θ3= 38.6822; θ4= 61.0450
11	θ1= 5.7392; θ2= 17.4576; θ3=30 ; θ4= 44.4270; θ5= 64.1581
13	θ1= 4.7802; θ2= 14.4775; θ3= 24.6243; θ4= 35.6853; θ5= 48.5904; θ6= 66.4435
15	θ1= 4.0960 ; θ2= 12.3736; θ3= 20.9248; θ4=30; θ5= 40.0052; θ6= 51.7868; θ7=68.2132
17	θ1= 3.5833; θ2= 10.8069; θ3= 18.2100; θ4= 25.9445; θ5= 34.2289; θ6= 43.4325; θ7= 54.3409; θ8= 69.6359
19	θ1= 3.1847; θ2= 9.5941; θ3= 16.1276; θ4= 22.8854; θ5=30 ; θ6= 37.7699; θ7=46.2383; θ8= 56.4427; θ9= 70.8119
21	θ1= 2.8660; θ2= 8.6269; θ3= 14.4775; θ4= 20.4873; θ5= 26.7437; θ6= 33.3670; θ7= 40.5416; θ8= 48.5904; θ9= 58.2117; θ10= 71.8051
23	θ1= 2.6053; θ2= 7.8375; θ3= 13.1366; θ4= 18.5530; θ5= 24.1477; θ6= 30.0000; θ7= 36.2215; θ8= 42.9859; θ9= 50.5994; θ10= 59.7274; θ11= 72.6586
25	θ1= 2.3880; θ2= 7.1808; θ3= 12.0247; θ4= 16.9578; θ5= 22.0243; θ6= 27.2796; θ7= 32.7972; θ8= 38.6822; θ9= 45.0995; θ10= 52.3415; θ11= 61.0450; θ12=73.4022
27	θ1= 2.2042; θ2= 6.6258; θ3= 11.0875; θ4= 15.6185; θ5= 20.2522; θ6= 25.0290; θ7= 30.0000; θ8= 35.2344; θ9= 40.8322; θ10= 46.9509; θ11= 53.8711; θ12=62.2042; θ13= 74.0576
29	θ1= 2.0467; θ2= 6.1506; θ3= 10.2866; θ4= 14.4775; θ5= 18.7493; θ6= 23.1324; θ7= 27.6640; θ8= 32.3924; θ9= 37.3832; θ10= 42.7321; θ11= 48.5904; θ12=55.2281; θ13= 63.2345; θ14= 74.6411
31	θ1= 1.9102; θ2= 5.7392; θ3= 9.5941; θ4= 13.4934; θ5= 17.4576; θ6= 21.5102; θ7= 25.6793; θ8= 30.0000; θ9= 34.5181; θ10= 39.2965; θ11= 44.4270; θ12=50.0555; θ13= 56.4427;θ14= 64.1581; θ15= 75.1649
33	θ1= 1.7908; θ2= 5.3794; θ3= 8.9893; θ4= 12.6356; θ5= 16.3348; θ6= 20.1055; θ7= 23.9695; θ8= 27.9532; θ9= 32.0900; θ10= 36.4236; θ11= 41.0145; θ12=45.9514; θ13= 51.3752; θ14= 57.5383; θ15= 64.9922; θ16= 75.6385
35	θ1= 1.6854; θ2= 5.0621; θ3= 8.4565; θ4= 11.8812; θ5= 15.3495; θ6= 18.8765; θ7= 22.4795; θ8= 26.1790; θ9= 30.0000; θ10= 33.9745; θ11= 38.1445; θ12=42.5685; θ13= 47.3321; θ14= 52.5720; θ15= 58.5330; θ16= 65.7504; θ17=76.0694
37	θ1= 1.5918; θ2= 4.7802; θ3= 7.9836; θ4= 11.2123; θ5= 14.4775; θ6= 17.7916; θ7= 21.1684; θ8= 24.6243; θ9= 28.1786; θ10= 31.8554; θ11= 35.6853; θ12=39.7090; θ13= 43.9830; θ14= 48.5904; θ15= 53.6639; θ16= 59.4416; θ17=66.4435; θ18= 76.4638
39	θ1= 1.5080; θ2= 4.5281; θ3= 7.5608; θ4= 10.6151; θ5= 13.7002; θ6= 16.8264; θ7= 20.0052; θ8= 23.2496; θ9= 26.5750; θ10= 30.0000; θ11= 33.5477; θ12=37.2478; θ13= 41.1395; θ14= 45.2778; θ15= 49.7434; θ16= 54.6655; θ17=60.2757; θ18= 67.0805; θ19= 76.8264
41	θ1= 1.4325 ; θ2=4.3012 ; θ3=7.1808 ; θ4=10.0787; θ5=13.0029 ; θ6=15.9620 ; θ7=18.9656 ; θ8=22.0243; θ9= 25.1507; θ10=28.3594 ; θ11=31.6682 ; θ12=35.0996 ; θ13=38.6822 ; θ14=42.4542 ; θ15=46.4688 ; θ16=50.8050 ; θ17=55.5885 ; θ18=61.0450 ; θ19=67.6684 ; θ20=77.1614.

3.   RESULTS AND DISCUSSION

Some obtained results are presented in this session with a comparison. Figure 2 show the output voltage waveform and Figure 3 show the harmonic spectrum of a 41-level inverter with EP method. Figure 4 show the 41-level inverter output waveform with HH method and Figure 5 show the harmonic spectrum analysis with HH method of a 41-level inverter. Table 3 shows the data comparison and Figure 6 show a graphic comparison of THDs between the EP method and HH method.
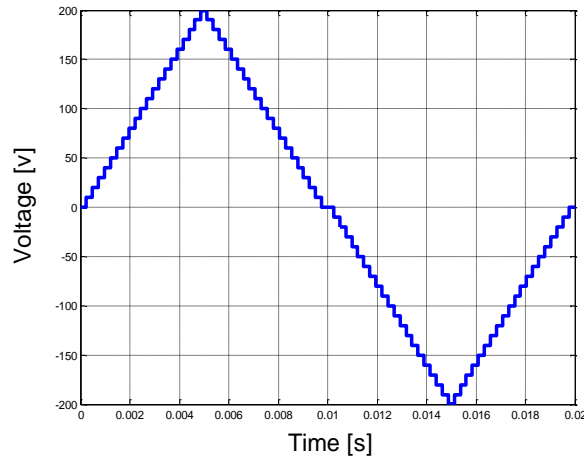

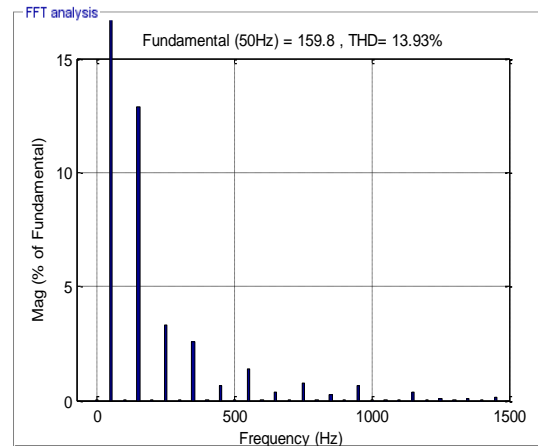Figure 2. The output voltage waveform of a 41-level inverter with EP method

Figure 3. THD Analysis of 41-Level output voltage with the EP method
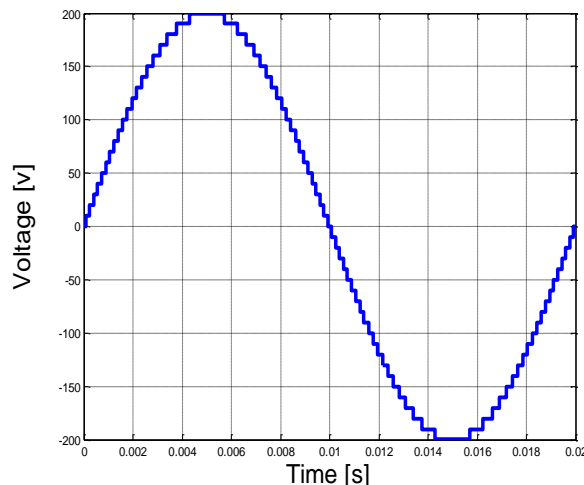

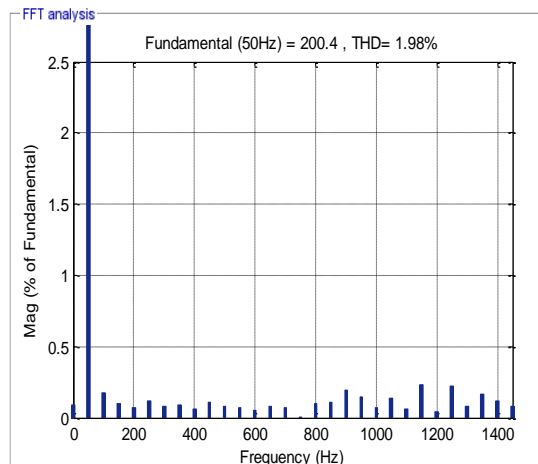Figure 4. Output voltage waveform for a 41-level inverter with the HH method

Figure 5. THD analysis of 41-level output voltage with the HH method

The Figure 2 and Figure 4 are the output voltage waveforms of the 41-level inverter with the two control methods, EP method and HH method, and the Figure 3 and Figure 5 are the total harmonic distortion THD of the 41-level inverter with the two methods respectively. From the analysis of THD comparison between the two control methods in Figure 6, we can say that there is a decrease of THD with an increase of inverter level, and for each inverter level, the THD with EP control method is higher than that obtained with HH control method. THD of the 17-level inverter with HH control method is down of 5 %, and with EP method is 18.15%. THD of a 41-level inverter with HH control method is 1.98 %, and with EP method is 13.93%. We note that the harmonic voltage is limited by the standard IEEE STD 519 [16]: The total harmonic distortion of voltage THDv<5%, and conclude that the HH method gives a good result with 17-level cascaded H-bridge inverter.

Table 3. THD with two methods, comparisons

Level	THD (%) with EP method	THD (%) with HH method
3	78.55	31.87
5	38.96	17.53
7	30.02	12.09
9	25.82	9.28
11	21.75	7.48
13	20.24	6.35
15	18.75	5.47
17	18.15	4.82
19	17.27	4.32
21	16.49	3.89
23	15.94	3.55
25	15.86	3.24
27	15.16	3.05
29	14.05	2.80
31	14.74	2.65
33	14.45	2.47
35	14.19	2.36
37	14.07	2.21
39	14.14	2.10
41	13.93	1.98

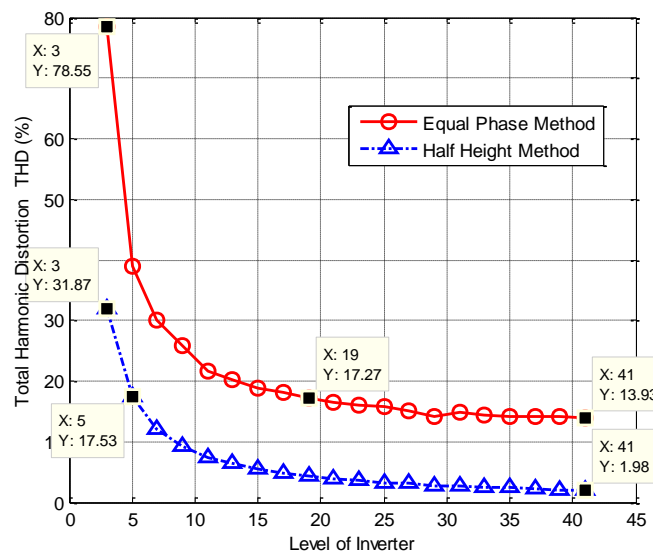Figure 6. THD comparison at different levels with the two control methods

4.   CONCLUSION

In this paper, contribution to the modeling and control of 41-level inverter using best switching angles calculation method is presented with two control methods. From simulation and THD compared results it has been observed that HH method is the best method for switching angles than the EP method.

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Alla Eddine Toubal Maamar received the B. Eng. degree and master degree in electrical engineering from University of Akli Mohand Oulhadj Bouira (UAMOB), Algeria, in 2014 and 2016, respectively. He is currently with the Department of Electrical Engineering and (LGEER) Laboratory, Hassiba Benbouali University of Chlef, Algeria. His research interests include the design, analysis and control of power electronic converters, electric machine control, multilevel inverters, artificial neural network (ANNs), robotics technology, renewable energy technologies.
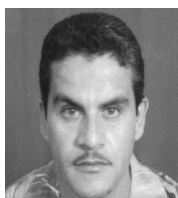
M'hamed Helaimi received the engineering degree in 2001, and magister degree in electrical engineering in 2004 from Hassiba Benbouali University, Chlef (UHBC), Algeria, and received the Ph.D. degree in electrical engineering from the University of Sciences and Technology of Oran (USTO), Bir El Djir, Algeria, in 2014. He joined the Department of Electrical Engineering, Chlef University, in 2004. His scientific work is related to dynamic modeling and control of nonlinear systems, genetic algorithms and artificial intelligence, induction heating applications and power electronics.

Rachid Taleb received the M.S. degree in electrical engineering in 2004, from Hassiba Benbouali University, and the Ph.D. degree in electrical engineering in 2011, from Djillali Liabes University, Algeria. He is currently an associate professor in the Department of Electrical Engineering, Hassiba Benbouali University, chlef, Algeria. He is also team leader of the Laboratoire Génie Electrique et Energies Renouvelables (LGEER) Laboratory. His research interests include power electronics, artificial intelligence control, heuristic optimization algorithms, and control theory of converters for renewable energy sources.

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