Implementation of Wavelet Modulation in Single Phase Inverter

V. Usha[1], K. Kathiresan[2], A. Ancimanonmary[3]

[1,2,3]*Assistant Professor,Department of EEE, VSB College of Engineering Technical Campus, Coimbatore, India*

Abstract-The real-time implementation and experimental performances of the wavelet-modulation technique for single-phase voltage-source inverters. The wavelet-modulation technique is realized through constructing a non dyadic-type multi resolution analysis, which supports sampling of a sinusoidal reference-modulating signal in a non uniform recurrent manner, then reconstructing it using the inverter-switching actions. The dilated and translated sets of wavelet basis functions used in the reconstruction are employed as switching signals to activate the inverter-switching elements. The wavelet-modulation technique is implemented in real time by using a digital signal processing board to generate switching pulses for a single-phase VS H-bridge (four-pulse) inverter. Experimental performances of the single-phase inverter, which is operated by the wavelet-modulation technique, are investigated while supplying linear load. Experimental test results show that high magnitude of fundamental components and significantly reduced harmonic contents of the inverter outputs can be achieved using the wavelet-modulation technique. The developed modulation technique is further demonstrated through performance comparisons with the pulse width modulation techniques for similar loading conditions.

Keywords—DC–AC power conversion, Fourier series, MOSFET, inverters, real-time systems and micro controller, wavelet Transforms.

I. INTRODUCTION

Inverters have emerged as an enabling technology over the past five decades. The high interests in optimizing and improving performances of inverters have been motivated by continuous demands for applications in various industrial sectors, such as motor drives, power systems, and renewable energy systems [1]. One of the objectives of these research efforts is to develop and experimentally test switching techniques, which are capable of operating inverters to produce outputs withhigher fundamental components and reduced harmonic contents regardless of their ratings, configurations, types and/or loading conditions [3]. There are several inverter-switching techniques reported in the literature, which have been developed and tested for operating both single-phase (1φ) and three-phase (3φ) inverters [2].These switching techniques have been developed to achieve the aforementioned operational features by satisfying the following constraints

1) Wide linear modulation range;

2) Minimum switching loss;

3)High overall inverter efficiency;

4)High magnitude of output fundamental component

5)Reduced output harmonic contents and minimum total harmonic distortion (THD) factors;

6) Simple implementation;

7) Economic considerations.

II. WAVELET-MODULATION TECHNIQUE

Wavelet transforms are gaining popularity in applications for energy systems and power electronics areas [5]. This popularity is originated from the ability of wavelet transforms to process signals that do not satisfy conditions of periodicity and/or stationary, which are required by conventional signal-processing methods like the Fourier transform [4]. These features of wavelet transforms have been employed in identifying and diagnosing different transient disturbances, detecting peak values of voltages and/or currents, initiating trip signals in protective relays, evaluating the performances of power electronic converters, selectingcontroller parameters, etc [6]. The utilization of wavelettransforms in operating inverters expands their applications inthe area of power electronics [20].

In general, the wavelet transform of any signal $x(t)$ is accomplished through successive extraction of all frequency components present in $x(t)$ using dilated and translated sets of wavelet basis functions. At each dilation (scale) j, one band of frequencies present in $x(t)$ can be extracted as [7].

$$[xp(t)]j \sum_{k\in z} x(t)\varphi(2j\ t-k), \quad j,k\in Z \tag{1}$$

Where $\varphi(t)$ is a scaling function, Z is the set of integer numbers is the inner product operation. The signal$[x(t)p\ ]j$ represents the projections of $x(t)$ on the spaces $Vj(\varphi)$, which are spanned by the φ 2*j* *t* *k* set of wavelet basis functions, and can be defined as [9]

$$Vj(\varphi) = clos_{L^2}\{\varphi(2j\,t - k)\}\ ,j,k\in Z \qquad (2)$$

The spaces spanned at all scales satisfy the nesting property as [10]:

$$0 \ldots \subset V0\ (\varphi) \subset V1\ (\varphi) \ldots \subset Vj(\varphi) \subset L2\ (R) \qquad (3)$$

of the MRA for $x(t)$ as a collection of all spanned spaces at all scales as [8]MRA

$$(x(t)) = \cup_{j\in z}(V_j(\varphi),\ Vj(\tilde{\varphi})) \qquad (5)$$

whereVj($\tilde{\varphi}$) is defined as

$$Vj(\tilde{\varphi}) = clos_{L^2}(\varphi\ (2^J\, t - k)),\ j,k\in Z \qquad (6)$$

2) dilations, which make them capable of constructing only dyadic type MRAs. These dyadic-type MRAs can only support uniform sampling-reconstruction processes, which can be expressed in terms of the decaying property of dyadic wavelet basis function as [9], [11], [13],

$$\varphi(2^J\, t - k) \rightarrow \delta(t),\ \text{for}\ j \rightarrow \infty \qquad (7)$$

Where $\delta\ (t)$ is the Dirac delta function.

III. EXPERIMENTAL PERFORMANCES

A new modulation technique, the wavelet-modulation technique, has been developed in correlation with the sampling based model of the 1φ *H*-bridge inverter [12]. This new modulation technique is realized through constructing a non dyadic type multiresolution analysis (MRA),which characterizes a nonuniform recurrent sampling reconstruction of continuous time signals using inverter-switching actions [14]. The non dyadic type MRA, which is required to realize the wavelet-modulation technique, is constructed as a collection of spaces spanned by dilated and translated wavelet basis functions, which are generated by the scale-based linearly combined scaling and synthesis scaling functions [19].

The performances of the 1φ voltage source (VS) *H*-bridge inverter operated by the wavelet-modulation technique (called the wavelet-modulated (WM) inverters) had been investigated in simulation for different load types supplied at a fixed frequency of 50 Hz. Moreover, simulated performances of the 1φ VS *H*-bridge WM inverters were compared with PWM inverters for similar loading conditions, as detailed in reference [15]. These simulated performances demonstrated encouraging abilities of the WM inverter to produce outputs with high magnitude of fundamental components, and low harmonic contents regardless of the load type [16], [17].

The objective of this paper is to provide a real-time implementation and to investigate the experimental performances of the wavelet-modulation technique for a 1φ VS *H*-bridge VS inverter when supplying different load types at different operating frequencies [21]. These experimental performances include the output voltage, load current, sensitivity to changing the output frequency, and the stability and accuracy of the constructed non dyadic MRA for operating practical inverters. Also, this paper aims to present comparative experimental performances of the developed wavelet-modulation technique with the carrier-based PWM technique for similar loading conditions.

IV. IMPLEMENTATIONOF WAVELET-MODULATION TECHNIQUE FOR SINGLE-PHASE INVERTERS

The wavelet-modulation technique for a single-phase (1φ) VS *H*-bridge inverter is realized through the successful construction of both parts of the non dyadic-type MRA. The realization of both parts implies sampling the sinusoidal reference-modulating signal *SM* (*t*) in a non uniform recurrent manner, and then generating switching pulses to activate the inverter for reconstructing *SM* (*t*) on its output. The THDV factor for a 1φ WM is shown in the Fig.1.

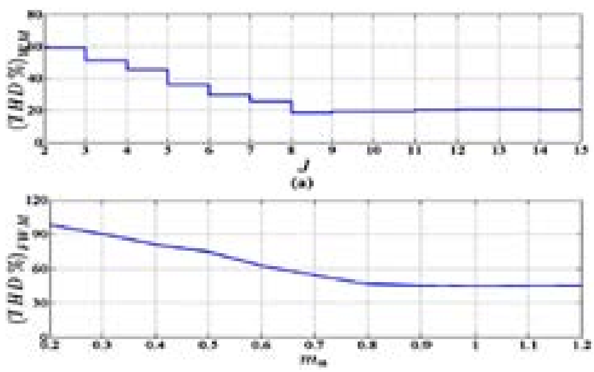

Fig.1. THD*V* factor for a 1φ WM

Fig.1. THD*V* factor for a 1φ WM and 1φ PWM inverters for an output frequency of 60 Hz. (a) THD*V* factor as a function in the maximum value of the scale *J* for the WM inverter. (b) THD*V* factor as a function in *ma* for the PWM inverter. Is developed to implement the wavelet-modulation technique for a 1φ VS *H*-bridge inverter in [18]. The step-by-step implementation procedure is made into a flowchart that is shown in Fig. 3. It is being noted that the condition $\gamma \leq 1$ is met only at the beginning or the end of each half-cycle of the inverter output voltage.

The value of $T\varphi$is determined using the changes in the dilation (scale) *j* over a quarter-cycle of *SM* (*t*) as follows:

$$\sum_{j=1}^{j} jT\varphi = \frac{T_m}{4} \quad (8)$$

Equation is an arithmetic series with its sum expressed as

$$\mathrm{T}\varphi \sum_{j=1}^{j} j = T\varphi\left(\frac{J^2+J}{2}\right) = \frac{T_m}{4} \quad (9)$$

$$\mathrm{T}\varphi = \frac{T_m}{2(J^2+J)} \quad (10)$$

The flowchart of Fig.2 is converted to a computer-executable program using a *pic micro controller*. When the code is executed, switching pulses are generated and applied to the gates of a1φ VS

H inverter.

Fig.2. Flowchart for the specific algorithm to implement the wavelet modulation technique for switching a 1φ *H*-bridge inverter. Tst = 40 μs. and

Tm is the period of *SM* (*t*).

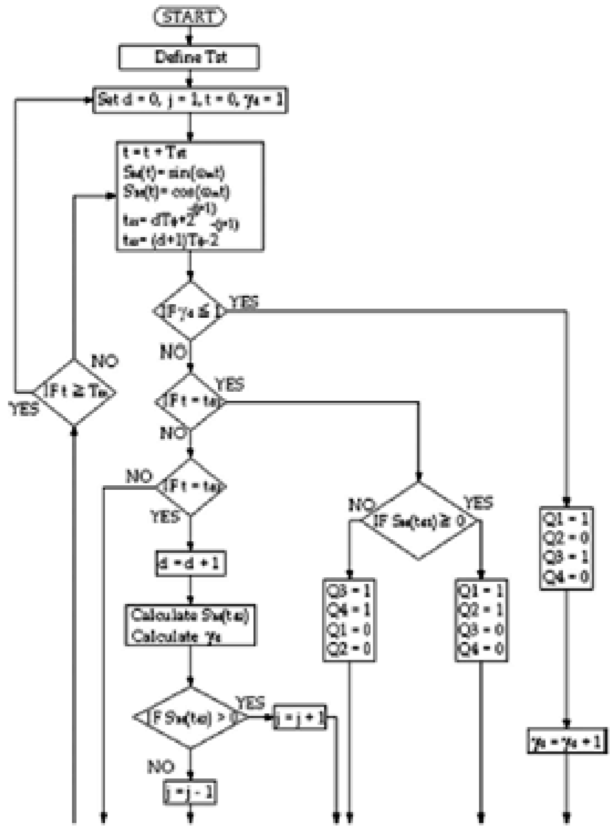

Fig.2. Flowchart to implement the wavelet modulation

The inverter-switching elements need switching times to fully change their status from ON to OFF, or OFF to ON [2], [3].These switching elements are activated by dilated and translated wavelet basis function generated by $\tilde{}\phi(t)$ that have their adjacent intervals of support placed such that

$$\mathrm{T}_{d1} = t_{sp} + t_{(d-1)} \quad (11)$$

wheretsp is the time interval separating the interval of support of $\tilde{}\phi$ _2*j* $t - (j - 1)$_ and $\tilde{}\phi$ _2(*j*+1)$t - ((j+1) - 1)$_. The set of time intervals *{t*sp*}*

j can provide the inverter MOSFET switching elements with their needed switching times [20].In this paper, the experimental performance tests were conducted using a 1-kW, 1φ VS 4-pulse MOSFET inverter for supplying the following loads:

1 an *R–L* load with an impedance of *ZL* = 10+*j*7.36 Ω (linear load);

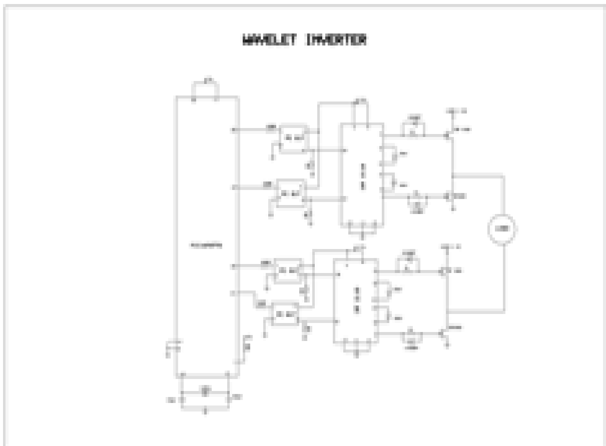

Fig.3. Experimental setup for the tested 1φ VS *H*-bridge MOSFET inverter

Fig.3 shows the schematic diagram of the experimental setup for the tested 1φ VS *H*-bridge MOSFET inverter and the tested load types.

Fig.4. Schematic diagram of the experimental setup for the single-phase (1φ) VS four-pulse MOSFET inverter and the tested load types. *Li* = 5 mH. Tested 1φ VS four-pulse MOSFET inverter was activated by switching Pulses generated by the PWM techniques for supplying the test load types. The PWM technique was implemented as the carrier-based type with a carrier frequency of *fc* = 1.8 kHz and a modulation index of *ma* = 0.85 [6], [8]. In addition, the tested RPWM technique was implemented with amodulation index of *ma* = 0.85, and a randomized carrier signal that had a frequency of *fc* = 1.8 kHz [2], [4]. It is worth mentioning that the selection of the carrier signal frequency *fc* was made on the basis of number of generated switching pulses over each cycle of *SM* (*t*) [20].

V. EXPERIMENTAL PERFORMANCES OF THE SINGLE-PHASEWAVELET-MODULATED INVERTER

The three test load types were supplied by switching pulses generated by the wavelet-modulation, carrier-based PWM and RPWM techniques for several inverter output voltage frequencies. The experimental test results for supplying the linear, dynamic and nonlinear loads by the three tested modulation techniques are provided in the following sections. It is noted that the term wavelet modulated (WM) is used when the inverter is activated using switching signals generated by using the wavelet-modulation technique. Also, the term pulse width modulated (PWM) is used when the inverter is activated using switching pulses generated by the PWM technique.

A. Output Frequency f = 50 Hz

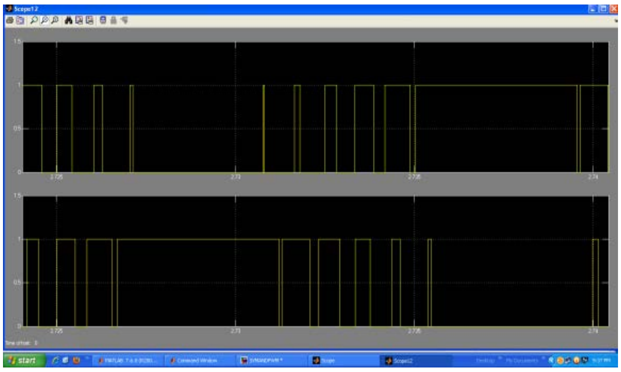

Fig. 4.*R–L* load experimental pulse generation waveform.

R–L Load: The open-loop steady-state experimental performance of the 1φ VS WM inverter feeding a linear load was investigated for supplying an *R–L* load. This experimental test was conducted for the inverter input dc voltage

*V*dc = 50 V.

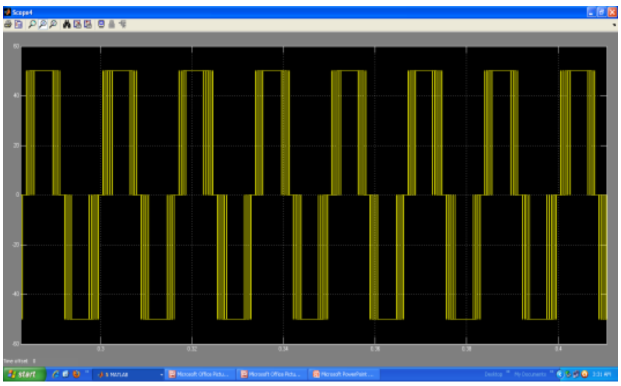

Fig.5. Performance of the 1φ pwm inverter supplying the *R–L* load at f = 50 Hz.

In addition, the tested *R–L* was supplied by the carrier-based PWM inverters with the same input dc voltage.

Output Frequency f = 50 Hz:

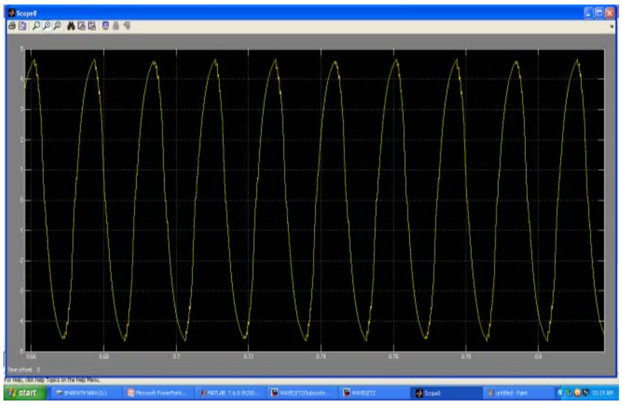

Fig.6 Performance of the 1φ pwm inverter supplying the *R–L* load at f = 50 Hz.

The above figures 4,5 and 6 shows the performance of the inverter i.e PWM based single phase inverter operation under various load condition . Here the load used for analyzing the performance of the inverter is both the resistive and inductive load with the operating frequency of 50Hz. The pulse generation waveform generation is also showed in the waveform content. It helps to understand the operation of inverter.

Component of the WM inverter outputs. Such feature of the wavelet-modulation technique ensured negligible energy distribution in the harmonic frequencies that resulted in low values of THD factors shown in figure 7. To further demonstrate the significance of thestable and convergent construction of the non dyadic MRA, the *R–L* load was tested for a step change in output frequency f = 50Hz with a fixed input dc voltage *V*dc = 50 V.

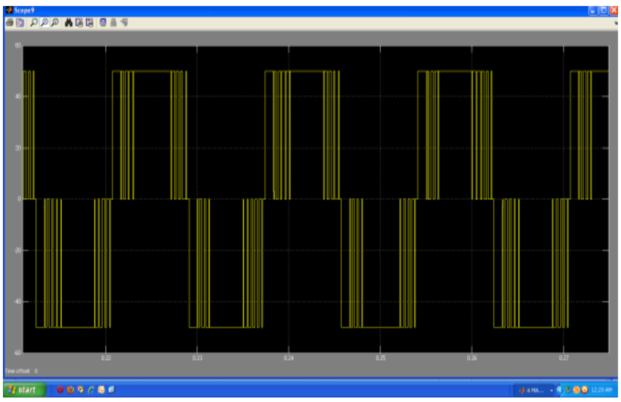

Fig.7. Experimental performance of the WM inverter supplying the *R–L* with current and output voltage.

Figure 7 shows the experimental output voltage *Vo*(*t*) of the WM inverter, and load current *IL* (*t*). The experimental results for the WM, which supplies a load with a step change in the output frequency, demonstrated stable the output voltage, and the load current responded to the change in the inverter's output frequency without errors, overshoots, or spikes. This section had presented experimental open-loop steady state performances of the 1*φ* VS *H*-bridge WM, PWM supplying linear, load. These experimental test results had provided the basis for performance comparison between the three tested inverter sunder similar loading conditions. In all performance tests, it had been found that the proposed WM inverter produced output voltage fundamental components with higher magnitudes than those obtained from the PWM inverters. Moreover, the output voltages and currents produced by the proposed WM inverter were found to have lower harmonic contents than those obtained from the other tested inverters.Furthermore,the real-time implementation of the wavelet-modulation technique had been found to require less memory and lower execution time than the PWM techniques. Finally, the features of the WM inverter outputs had shown negligible sensitivity to inverter output frequency, even under sudden changes in the inverter output frequency, which was due to the stable and convergent characteristics of the constructed non dyadic MRA.

VI. CONCLUSION

This paper had presented the real-time implementation and experimental performances of the single-phase VS *H*-bridge WM inverter for supplying different load types at different frequencies. The wavelet-modulation technique had been successfully implemented as a non dyadic MRA, which was constructed using the scale-based linearly combined scaling and synthesis scaling functions. Experimental performances of the WM inverter had demonstrated significant abilities to produce outputs with high fundamental component magnitude and low harmonic contents, when supplying various load types at different frequencies. Also, performance comparisons of the WM with the PWM inverters had clearly demonstrated the ability of the WM inverter to outperform the PWM inverters for similar loading conditions. The experimental performances along with simple Real-time implementation provided evidence for the suitability and applicability of the WM inverters for various industrial applications.

REFERENCES

[1] K. Bose, "Power electronics and motor drives recent progress and perspective," *IEEE Trans. Ind. Electron*., vol. 56, no. 2, pp. 581–588, Feb. 2009.

[2] X.Mao, R. Ayyanar, and H. K. Krishnamurthy, "Optimal variable switching frequency scheme for reducing switching loss in single-phase inverters based on time-domain ripple analysis,*" IEEE Trans. Power Electron., vol. 24, no. 4, pp. 991–1001, Apr. 2009.*

[3] A. M. Salamah, S. J. Finney, and B. W. Williams, "Single-phase voltage source inverter with a bidirectional buckboost stage for harmonic injectionand distributed generation," IEEE Trans. Power Electron., vol. 24, no. 4, pp. 376–387, Feb. 2009.

[4] Y. C. Lim, S. O. Wi, J. N. Kim, and Y. G. Jung, "A pseudorandom carrier modulation scheme," *IEEE Trans. Power Electron.*, vol. 25, no. 4, pp. 797–805, Apr. 2010.

[5] R. Sharma and J. A. R. Ball, "Unipolar switched inverter low-frequency harmonics caused by switching delay," *IET Power Electron*., vol. 2, no. 5,pp. 508–516, 2009.

[6] S. R. Bowes and D. Holliday, "Optimal regular-sampled PWM inverter control techniques," *IEEE Trans. Ind. Electron*., vol. 54, no. 3, pp. 1547–1559, Jun. 2007.

[7] J. Salmon, A. M. Knight, and J. Ewanchuk, "Single-phase multilevel PWM inverter topologies using coupled inductors," *IEEE Trans. PowerElectron*., vol. 24, no. 5, pp. 1259–1266, May 2009.

[8] S. de Freitas, C. B. Jacobina, and E. C. dos Santos, "Single-phase to single-phase full-bridge converter operating with reduced AC Power in the DC-link capacitor,*" IEEE Trans. Power Electron., vol. 25, no. 2, pp. 272–279, Feb. 2010.*

[9] S. Kim, Y. G. Jung, and Y. C. Lim, "A new hybrid random PWM scheme," *IEEE Trans. Power Electron.*, vol. 24, no. 1, pp. 192–200, Jan.2009.

[10] Hobraiche, J. P. Vilain, P. Macret, and N. Patin, "A *new* PWM strategy to reduce the inverter input," *IEEE Trans. Power Electron*., vol. 24, no. 1,pp. 172–180, Jan. 2009.

[11] F. Zhang and Y. Yan, "Selective harmonic elimination PWM control scheme on a three-phase four-leg voltage source inverter," *IEEE Trans.Power Electron*, vol. 25, no. 7, pp. 1682–1689, Jul. 2009.

[12] G. Poddar and M. K. Sahu, "Natural harmonic elimination of square-wave inverter for medium-voltage application,*"*EEE Trans. Power Electron*, vol. 24, no. 5, pp. 1182–1188, May 2009.*

[13] Odavic, M. Sumner, P. Zanchetta, and J. C. Clare, "A theoretical analysis of the harmonic content of PWM waveforms for multiple-frequency modulators,"*IEEE Trans. Power Electron.*, vol. 25, no. 1, pp. 131–141,Jan. 2010.

[14] K. M. Rahman, M. K. Rezwan, M. A. Choudhury, and M. A. Rahman, "Variable-band hysteresis current controllers for PWM voltage-source inverters," *IEEE Trans. Power Electron.*, vol. 12, no. 6, pp. 964–970, Nov. 1997.

[15] A. Z. lbanna and C. J. Hatziadoniu, "Harmonic modeling of hysteresis inverters in frequency domain," IEEE Trans. Power Electron., vol. 25, no. 5, pp. 1110–1114, May 2010.

[16] S. A. Saleh, C. R. Moloney, and M. A. Rahman, "Development and testing of wavelet modulation for single-phase inverters," *IEEE Trans.Ind. Electron*., vol. 56, no. 7, pp. 2588–2599, Jul. 2009.

[17] S. A. Saleh and M. A. Rahman, "Analysis and real-time testing of a controlled single phase wavelet-modulated inverter for capacitor-run induction motors," *IEEE Trans. Energy Convers*., vol. 24, no. 1, pp. 21–29, Mar. 2009.

[18] Gonz´alez, D. , J. T. Bialasiewicz, J. Balcells, and J. Gago, "Wavelet based performance evaluation of power converters operating with modulated switching frequency," *IEEE*

Trans. Ind. Electron., vol. 55, no. 8, pp. 3167–3176, Aug. 2008.

[19] R. Yang, B. Zhang, D. Qiu, and Z. Liu, "Time frequency and wavelet transforms of EMI dynamic spectrum in chaotic converter," *IEEE Trans.Power Electron, vol. 24, no. 4, pp. 1083–1092*, Apr. 2009.

[20] Coppola, L. Qian, S. Buso, D. Boroyevich, and A. Bell, "Wavelet transform as an alternative to the short-time Fourier transform for the study of conducted noise in power electronics," *IEEE Trans. Ind. Electron., vol. 55, no. 2, pp. 880–887, Feb. 2008.*

[21] K.Kathiresan, N.R.Naharaj, R.Thangaraj, "Implementation of Hybrid Algorithm for solving OPF problem in a Distribution system Environment,"*IJCTA, 9(5), pp. 443–448,2016.*