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Design and Implementation of an Electronic Fan Regulator for Reduced Harmonics and Ripple Free Speed

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Abstract: Majority electronic fan regulators available in the market feed significant amounts of harmonics into the fan, which leads to fan overheating and frequent failures of fan capacitors. This paper presents a design and development of a new electronic fan regulator that feeds negligible amounts of harmonics into the fan, and hence offers more reliable fan operation with smooth control and ripple free speed.

The paper first reviews different forms of power electronic based control applicable to single-phase induction motors, and then identifies six topologies suitable for ceiling fans, based on the simplicity and cost effectiveness in meeting the performance targets. Final topology for the new design was selected after simulation of each short-listed topology to assess relative performances in terms of lesser harmonics, ripple free speed, smooth control, and cost. Finally, a prototype was built of the selected topology for a 70W single phase ceiling fan and test results verified the simulation results. Details of investigations, design, simulation, and test results are given and discussed.

Keywords: Ceiling Fan, Fan Regulator, Harmonics, PWM, Speed Ripples

1. Introduction

Majority home appliances use single phase induction motors to convert electrical energy to rotational energy. This energy is needed for various day-to-day activities including washing, water pumping, air flow control, etc. Ceiling fan is one of the most common appliances used in almost all households to obtain comfort through air flow control.

To do the air flow control, ceiling fan uses a regulator circuit. It controls the speed of the ceiling fan and thereby the air flow. Several fan regulator (FR) circuits are available in the market including,

- Resistive type FR
- Capacitive type FR
- Electronic type FR
- Inductive type FR [1], [3]

A compact design and stepless control are achieved using an electronic type FR since it incorporates an adjustable chopping of AC voltage waveform with lesser number of electronic components. However, it has several drawbacks, including mechanical oscillations, humming noise, speed ripples, fan overheating, and frequent failures of fan capacitor. Additionally, these FRs generate voltage and current harmonics back to the utility system which can add on to a significant burden. Most of these problems occur due to poor quality voltage waveforms generated by these FRs at the fan terminals.

With the advancement of power electronics and control technologies, diverse methods of single-phase motor controllers have been identified, in general, and some of these methods are readily applicable to control the speed of ceiling fans, subjected to their performance and implementation cost. The aim of this paper is to investigate a power electronic based better alternative to the existing traditional electronic fan regulator (TEFR) but at an affordable price.

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2. Present Status of Fan Regulators

Phase angle control method using triac or back-to-back thyristors is the simplest and conventional technique used in electronic FRs [3]. Extinction angle control, or PWM control methods using two bi-directional power switches, one in series with the fan and the other in parallel with the fan, offer improved performances over the phase angle control [2]. Figure 1 shows one form of this power circuit, but other forms of implementations are possible (e.g., using two power MOSFETs and two full bridge diode rectifiers). A damped input filter is necessary when using PWM control to eliminate pulsating current at the supply side. This form of electronic FR is treated as a cost-effective option.

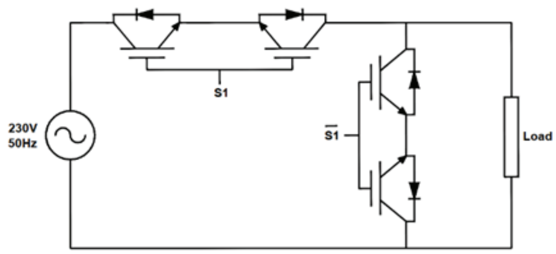


Figure 1 - Topology using Two Bi-Directional Switches

H-bridge configured IGBT converter topology shown in Figure 2 is also a promising option for an electronic FR [4]. This is in fact an AC-AC buck converter and operated with PWM control to minimizes harmonics in the fan voltage. Harmonic Elimination PWM has been successfully implemented with this topology [3] to remove 3rd, 5th, and 7th harmonics from the fan voltage, so that the hum at low speeds is eliminated. Some implementations incorporate remote control facility too for further attractions by the users. However, limited speed control range seems to be a common concern for lots of these topologies.

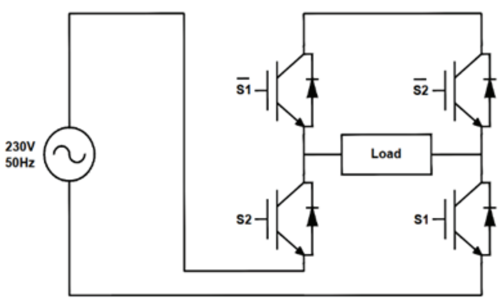


Figure 2 - AC-AC Buck Converter Topology

Several other power circuit topologies listed in Table 1 are considered for electronic FRs, each having its own merits and demerits as listed [3],[4],[5],[6],[7].

Table 1 - Comparison of Various Single-Phase Motor Controlling Methods

Method of Control	Review
DC chopper converter	Cheap, simple control, No DC link capacitor
Burst firing converter	Less harmonic content, High I_{start} at cycles
AC-AC buck converter	Cheap, Ease of harmonic filtration
Non-conventional cyclo-converter	Wide speed range, cheap
Conventional cyclo-converter	Wide speed range, Intermediate control complexity
Single phase PWM inverter with full bridge rectifier	Wide speed range, Different PWMs can be implemented, Large DC link capacitor
Single phase PWM inverter with half bridge rectifier	Divided DC bus, reduced torque & speed pulsations
Single phase PWM inverter with controlled half bridge rectifier	Active rectifier for current control, regenerative capability, can increase utility side power factor
Two-phase full bridge PWM inverter	Complex method of controlling, Precise control of speed and torque
Two phase half bridge PWM inverter	Motor windings receive half of the supply voltage, need to keep balanced voltage across DC link capacitors
Two phase semi-full bridge PWM inverter	Complex method of controlling, divided DC bus is absent
Two phase PWM inverter with controlled rectifier	Costly, can implement space vector PWM, supply power factor and THD can be controlled

3. Methodology

3.1 Shortlisted Motor Controllers

Principal criteria adopted in the development of electronic FR described in this paper are reduced complexity in power circuits, less space for the overall circuit and justifiably affordable price. After going through the literature extensively, six methods were shortlisted for further investigations of performances at depth. The selected methods were:

- DC chopper fed converter method
- Burst firing converter method
- Non-conventional cycloconverter method
- AC-AC buck converter method
- Single-phase PWM inverter with half bridge rectifier method
- Single-phase PWM inverter with full bridge rectifier method

3.2 Load Modelling

Investigation of the shortlisted methods were done in Matlab/Simulink software environment. A reliable and better model of the ceiling fan was a necessity, and this was developed based on the ceiling fan motor parameters given in [8]. Figure 3 shows the simulation model and Table 2 lists the parameters used.

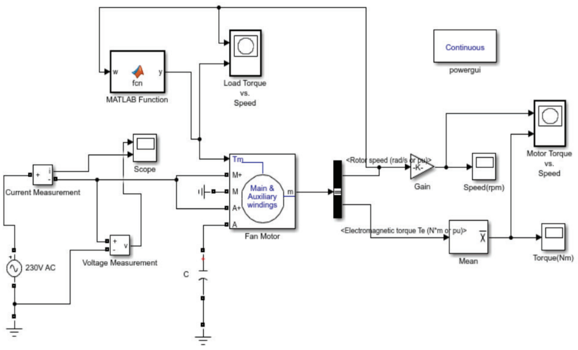


Figure 3 - Modelled Ceiling Fan in Simulink

Table 2 - Ceiling Fan Motor Parameters

Parameter	Symbol	Value
Main winding resistance	r_{1m}	300 Ω
Auxiliary winding resistance	r_{1a}	320 Ω
Rotor resistance	r_2'	290Ω
Main winding leakage reactance	x_{1m}	170 Ω
Auxiliary winding leakage reactance	x_{1a}	223 Ω
Rotor leakage reactance	x_2'	170 Ω
Magnetizing reactance	$x_{mag.}$	711 Ω
Pole pairs	p	9
Split capacitor value	C	2.5uF

The motor model was validated by conducting some experimental tests on the motor and simulating the same test conditions using the model and observing the agreement between the two. Simulated no load speed (without blades) is 329 rpm, which is in agreement with synchronous speed 333.3 rpm for 50 Hz operation of the 18-pole motor. T-ω characteristics of the motor with 2.5 uf capacitor in series with auxiliary winding was measured, which was same as that simulated. Figure 4 shows measured and simulated speed versus voltage plots for 50 Hz, operation of the fan, which indicates very close agreements between the two. The speed at 230 V operation was 288 rpm.

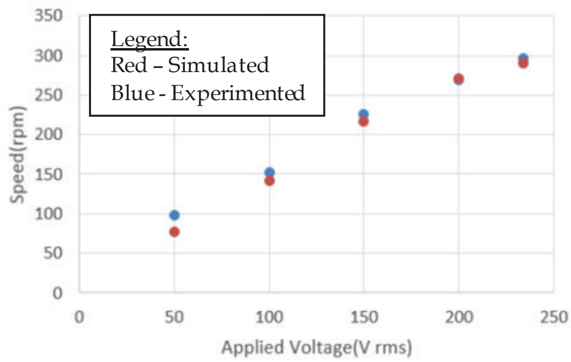


Figure 4 - Motor Speed vs. Applied Voltage

The rest of the methodology presented assesses the performance of each topology by simulating each topology and comparing the results with those for the traditional electronic fan regulator (TEFR). Moreover, a cost analysis is carried out to check whether the proposed solution can be implemented as a market competitive product.

3.3 Modelling of TEFR

This topology (Figure 5) incorporates a TRIAC which electronically chops a portion of supply waveform and thereby controlling the applied voltage to the ceiling fan. Two back-to-back thyristors were used to model the TRIAC. DIAC was realized using an electrical switch which closes when the voltage across two terminals is higher or lower than predefined values.

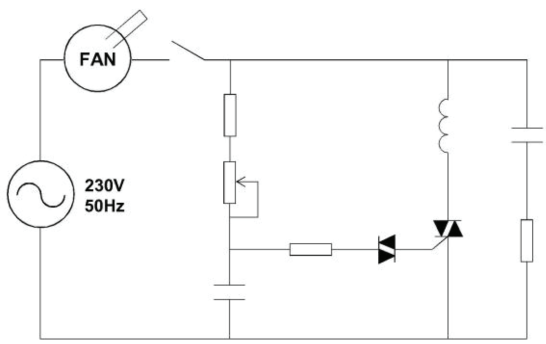


Figure 5 - Circuit Diagram of a TEFR

Four parameters were recorded at 170 rpm, 200 rpm, 230 rpm, 260 rpm and 288 rpm using this model to analyze its performance. Those parameters are THD_V, THD_I, maximum input current to the fan and time taken to stabilize at a certain speed level starting from 0 rpm (stabilization time). Observed current and voltage waveforms at 260 rpm are shown in Figures 6 and 7, respectively.

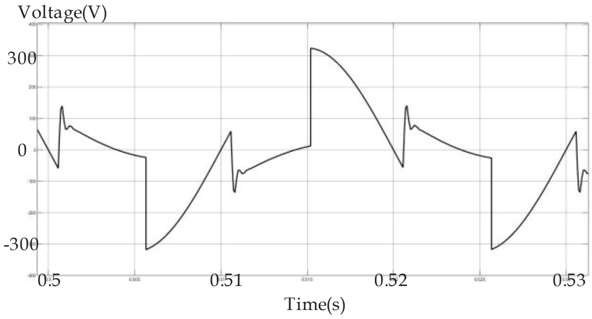


Figure 6 - Output Voltage Waveform of TEFR at 260 rpm

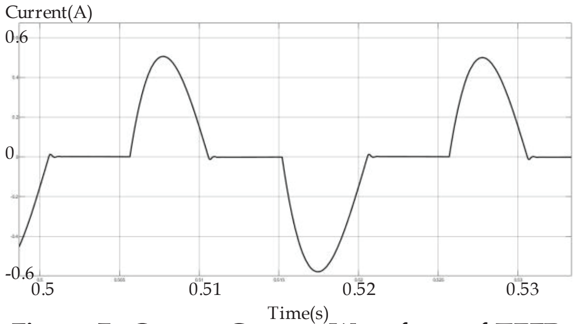


Figure 7 - Output Current Waveform of TEFR at 260 rpm

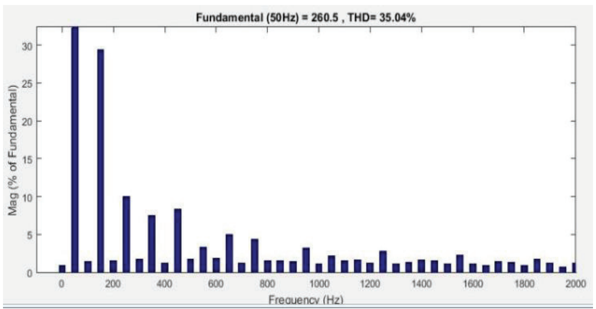


Figure 8 - FFT Analysis of Output Voltage of TEFR at 260 rpm

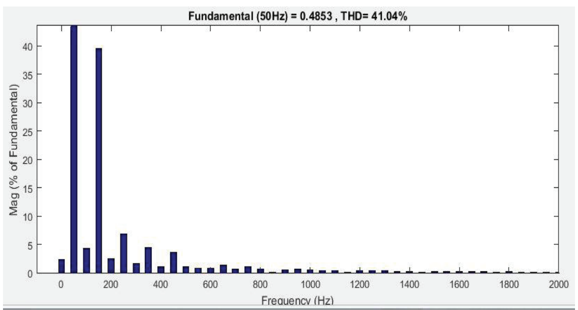


Figure 9 - FFT Analysis of Output Current of TEFR at 260 rpm

FFT (Fast Fourier Transform) analysis of voltage and current for this topology is given in Figures 8 and 9. It is clear that the output voltage and current waveforms of this FR contain significant level of harmonics.

Because of discontinuous current waveforms, torque produced by the motor varies heavily, resulting in speed ripples. Also, Cu losses are high since the current harmonics are significant.

3.4 Modelling of DC Chopper Fed Controller

Figure 10 shows circuit diagram and simulated DC chopper fed controller. Q1 and Q2 are active switches realized using MOSFETs. Switching signal generator and Boolean logic generate complementary switching signals for Q1 and Q2, respectively.

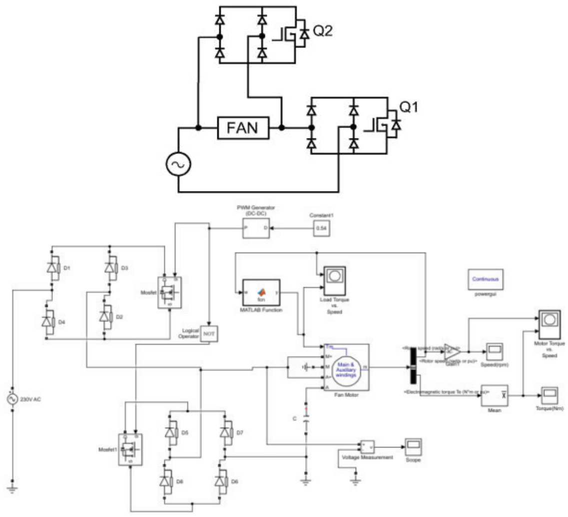


Figure 10 - Circuit Diagram and Modelled DC Chopper Fed Controller

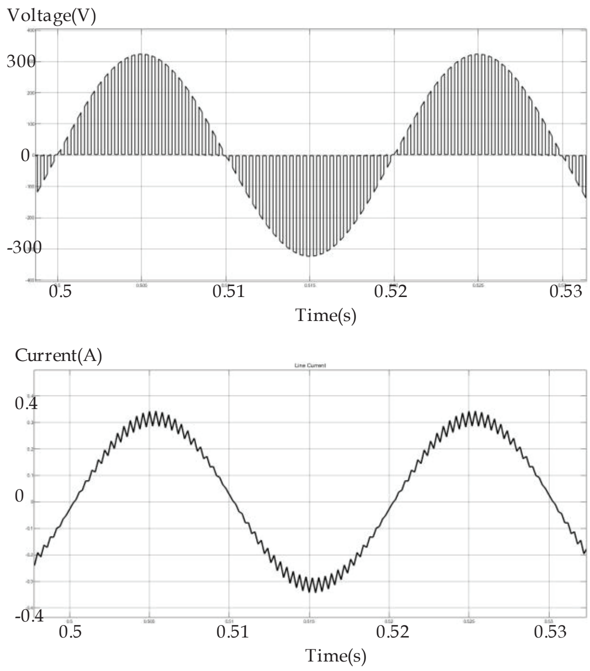


Figure 11 - Load Voltage (upper) and Current (lower) Waveforms at 260 rpm

Compared to TEFR, this topology generates much lower contents of current harmonics. Also, load receives current continuously (Figure 11).

Moreover, for every PWM topology discussed, 2.5 kHz switching frequency was used to check the performance.

3.5 Modelling of Burst Firing Method

This method controls the speed of the ceiling fan by cycle switching of voltage waveform. Separate zero crossing detector technique determines the starting point of burst cycle. Circuit diagram and simulated model are shown in Figure 12.

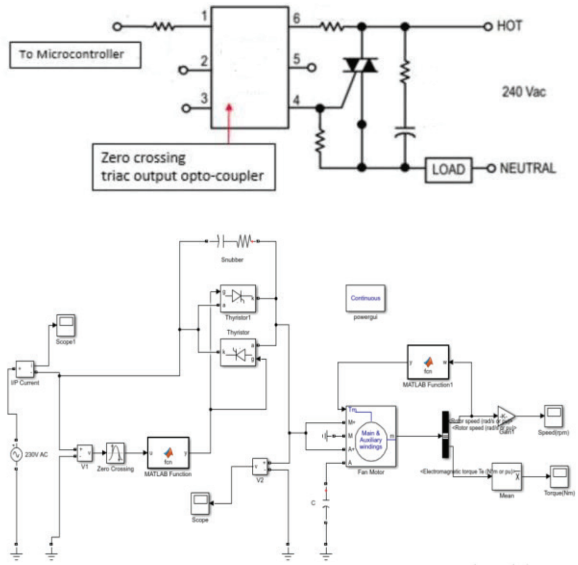


Figure 12 - Circuit Diagram and Modelled Burst Firing Method

Although this method shows relatively minimum harmonic distortions at the output, it possesses two major drawbacks. Since it starts a cycle at zero voltage point, starter capacitor of the ceiling fan absorbs high starting current at the beginning of the cycle. This phenomenon can deteriorate the starter capacitor. Moreover,

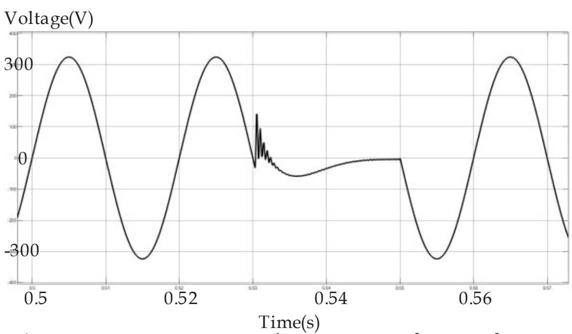


Figure 13 - Output Voltage Waveform of Burst Firing Method at 260 rpm

some noise can be seen in the cut-off points of the voltage waveform (Figure 13). This noise can be somewhat high in the practical implementation. It causes subharmonics and those are very difficult to filter using low-cost filters.

3.6 Modelling of Non-Conventional Cyclo-Converter (NCCC)

This topology consists of 3 main circuits, namely, power switching circuit, controller circuit and zero crossing detector circuit (Figure 14). By changing the frequency through the controller circuit, it is possible to change the ON and OFF times of the power switches. Since the source polarity changes in every 10ms of time, a separate switching algorithm needs to be developed to preserve same ON, OFF times for the active switches Q1, Q2, Q3 and Q4. There can be four different states according to Table 3.

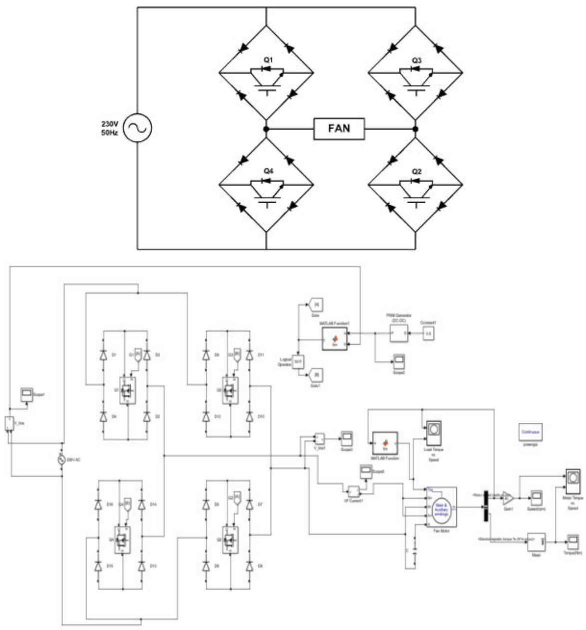


Figure 14 - Circuit Diagram and Modelled Non-Conventional Cyclo-Converter

Table 3 - Developed Switching Algorithm

Output state of frequency generator	Source voltage polarity	Activated switch
1	+	Q1, Q2
1	-	Q3, Q4
0	+	Q1, Q2
0	-	Q3, Q4

Figure 15 shows load voltage (upper) and current (lower) waveforms generated from this topology. When compared to other techniques, it has high harmonic content at the output.

Nevertheless, this technique offers wider speed range and quick stabilization times.

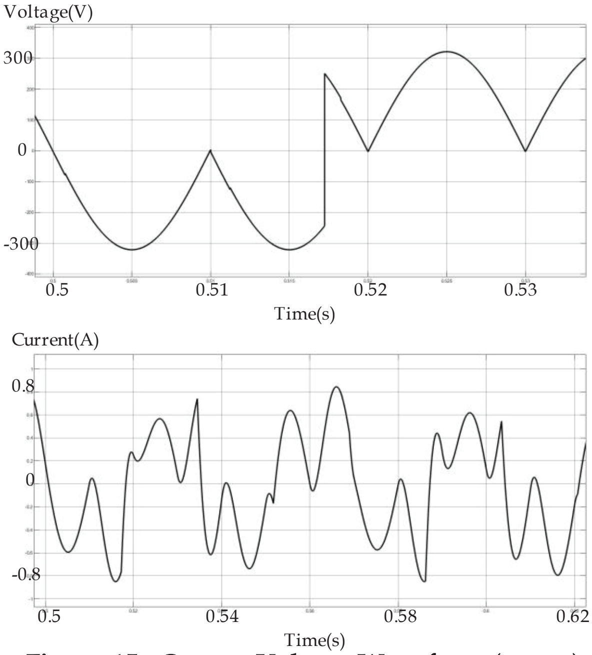


Figure 15 - Output Voltage Waveform (upper) and Output Current Waveform (lower) from Non-Conventional Cyclo-Converter Method at 260 rpm

3.7 Modelling of AC-AC Buck Converter Method

This method follows the circuit topology given in Figure 2, in that the bi-directional switch pairs Q1&Q2 and Q3&Q4 are operated in complementary form with PWM switching to control the effective voltage to the fan. Matlab/Simulink model of this circuit is shown in Figure 16.

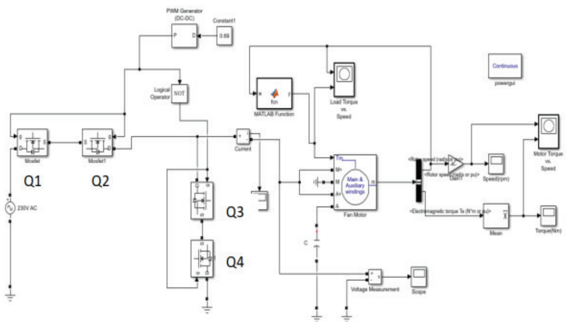


Figure 16 - Modelled AC-AC Buck Converter

Simulation results suggest that the stabilization times are moderate with this technique. Other than that, voltage and current harmonics are very minimal. The results obtained are very much similar to DC chopper fed controller.

3.8 Modelling of Single-Phase PWM Inverter with Half Bridge Rectifier (1 Ph. PWM HBR)

Figure 17 shows the circuit diagram and the modelled controller in Matlab/Simulink. The AC supply is converted to DC using diodes and smoothed using DC link capacitors. Sinusoidal PWM scheme was used to drive the MOSFETs.

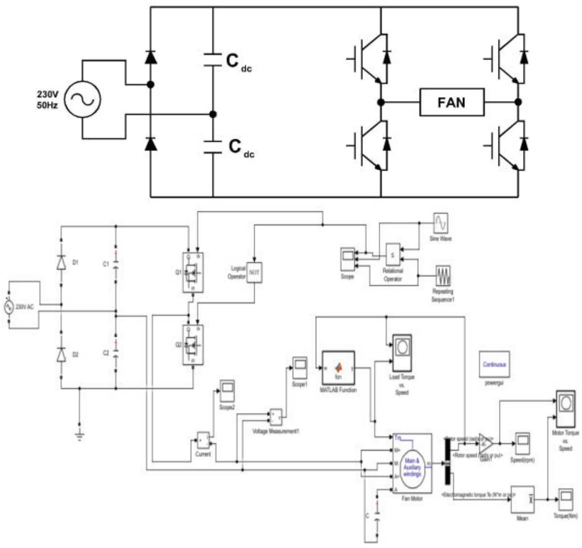


Figure 17 - Circuit Diagram and Modelled Single-Phase PWM Inverter with Half Bridge Rectifier

This method presented very good stabilization times compared to all previously described methods. In comparison with non-conventional cyclo-converter method and burst firing method, this topology shows less voltage and current harmonics.

3.9 Modelling of Single-Phase PWM Inverter with Full Bridge Rectifier (1Ph PWM FBR)

In this method, a fully rectified AC supply is sent through two level single-phase inverter (Figure 18).

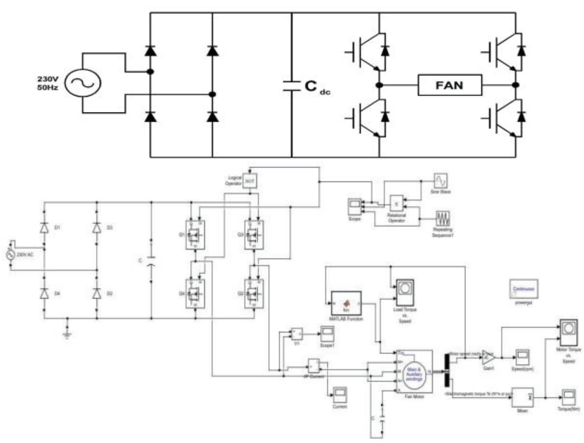


Figure 18 - Circuit Diagram and Modelled Single-Phase PWM Inverter with Full Bridge Rectifier

Same PWM scheme is used as previous. Fan speed can be changed by changing the reference frequency.

As same as the previous method, this method shows very good stabilization times and less voltage and current harmonic content (Figure 19). The DC link capacitor size was chosen such a way that it produces same ripple as previous method.

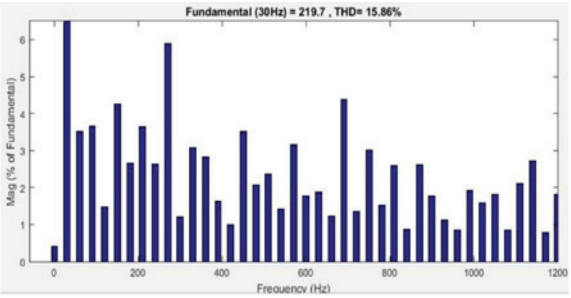


Figure 19 - FFT Analysis of Output Current Harmonics at 260 rpm

3.10 Cost Analysis of Proposed Fan Regulators

Table 4 - Cost Estimation of DC Chopper Fed Controller

Item	P.U. Cost (Rs.)	No.	Cost (Rs.)
Mosfets	65	2	130.00
Diodes For Rectification	5	8	40.00
Snubber Res	8	2	16.00
Snubber Cap	4	2	8.00
Pull down Res	1	2	2.00
Gate Res	1	2	2.00
Anti-Parallel Gate Diode	5	2	10.00
Inductors	40	2	80.00
Bypass Caps	1	3	3.00
Res. For IR side	1	2	2.00
Opto-isolators	100	2	200.00
Microcontroller	330	1	330.00
Reset Res.	1	1	1.00
Oscillator	11	1	11.00
Caps for Oscillator	1	2	2.00
Remote Controller kit	180	1	180.00
1 way 1 gang switch	175	1	175.00
SMPS	90	3	270.00
Enclosure	263	1	263.00
Other	86	1	86.00
Total			1811.00

Cost of production of each fan regulator is an important parameter in the comparison. A production cost calculation was performed for each FR and compared the results with the production cost of TEFR. Table 4 gives an example detailed cost estimation for the DC chopper fed FR, which is 1811 LKR. Labour cost, soldering, etc. is reflected in 'other' category of the table. The production cost of market available TEFRs were also estimated and it was around 862 LKR.

3.11 Performance Analysis and Cost Comparison

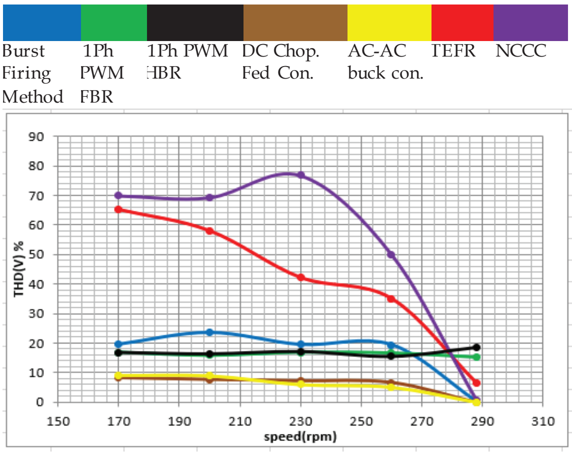
The four plots in Figure 20 show the variations of THD_V, stabilization time, maximum input current, and THD_I, all against speed, for the six short-listed FRs, together with that for the TEFR.

According to the plots of THD_I and THD_V, TEFR and non-conventional cyclo-converter methods show high harmonic content at low speeds. Hence non-conventional cyclo-converter method was kept aside.

Burst firing method shows considerably high input current at the very first burst of the cycle. Since the split capacitor of the ceiling fan has de-energized in the off period, it takes high current at the beginning. Also, this method shows sub harmonics which are very difficult to filter, and this can be even higher in practical implementation.

Referring to Figure 20-2, single-phase full-bridge sinusoidal PWM inverter, and single-phase half-bridge sinusoidal PWM inverter offer impressive stabilization times. Also, these two methods show comparatively less harmonic content (Figures 20-1 and 20-4). However, both these methods have high production cost values (around 2971 LKR for 1Ph PWM FBR and 3031 LKR for 1Ph PWM HBR). This is mainly due to costly DC link capacitors.

Hence, after consideration of all these facts, DC chopper fed controller and AC-AC buck converter methods seem to meet the objectives stated in the introduction. By comparing the cost of these two methods, it was decided that the DC chopper fed controller offers slightly low production cost than the AC-AC buck converter (around 1955 LKR). Accordingly, the DC chopper fed controller was selected for the prototype implementation.



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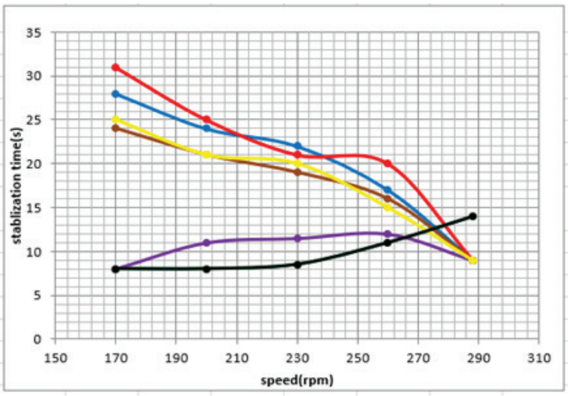

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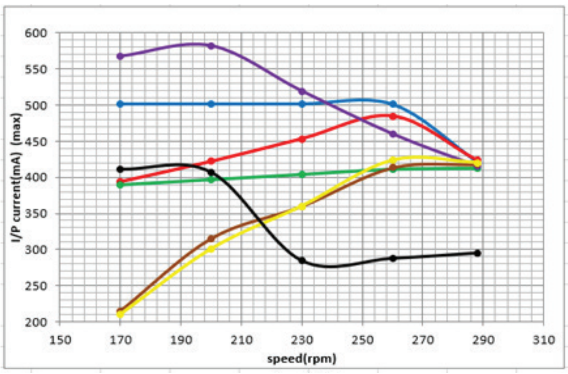

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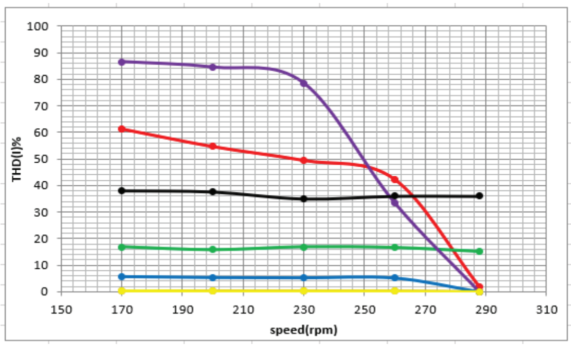

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Figure 20 - Performance Comparison of Proposed FRs with TEFR

3.12 Prototype of DC Chopper Fed Controller

A prototype was developed for the DC chopper fed fan regulator to test performance and validate the results obtained from simulations. An ATmega 328P microcontroller was used to create complementary switching signals of 2.5 kHz frequency for the two MOSFETs. In order to prevent any shoot-through, 2 μs software based dead time was introduced. Since the direct microcontroller switching signal is not suitable for driving MOSFETs, two gate driver ICs (TLP250) were used to drive the MOSFETs. These ICs not only drive MOSFETs efficiently with internally set push-pull configuration, but also isolate the signal side from power side. Developed PCBs for signal and power circuits are shown in Figure 21. An LC input filter was used to remove high frequency ripple-current in the source side.

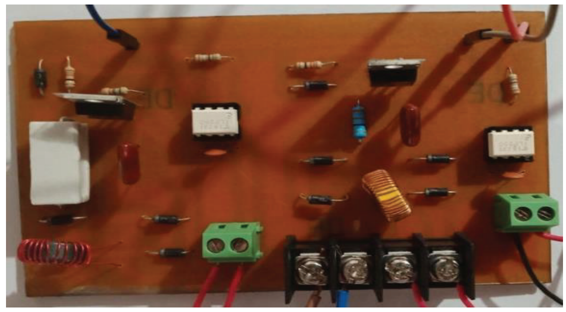

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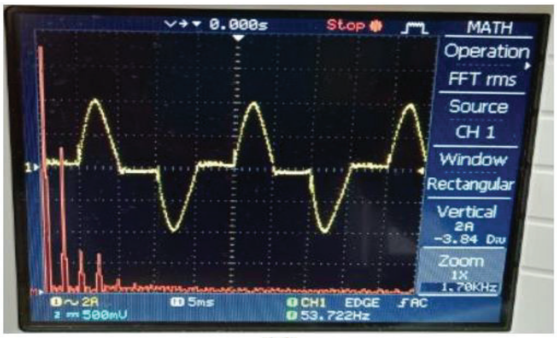
Figure 21 - (1) Power PCB and (2) Signal PCB

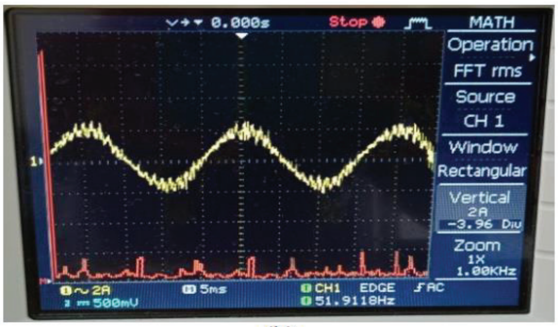
4. Results and Discussion

A 70W permanent split capacitor type ceiling fan motor was used as the load to check the performance of DC chopper fed controller and TEFR. Load voltage, current and generated waveforms were recorded for comparison.

Figure 22 shows load current waveforms at 100 rpm and 160 rpm for the proposed fan regulator. For comparison purposes, the load current waveforms for the TEFR for same speeds are also given alongside. It is clear that the DC chopper fed controller supplies continuous sinusoidal current to the load whereas the TEFR supplies discontinuous current. This makes the ceiling fan run smoothly with the proposed fan regulator without speed ripples and obtain quick speed stabilizations.

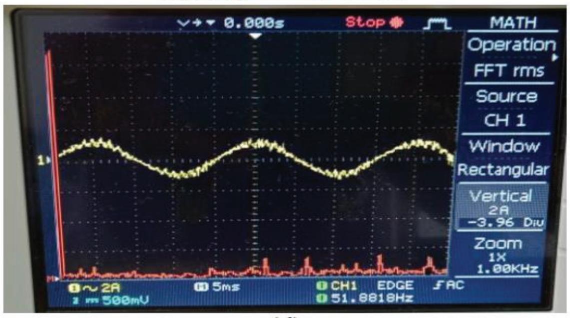


(a)
Load current waveform of Traditional EFR @160rpm 200mA/div



(b)
Load current waveform of proposed circuit @160rpm 200mA/div

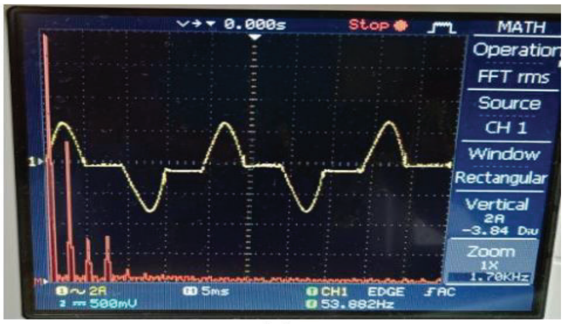
(c)
Load current waveform of Traditional EFR @100rpm 200mA/div



(d)
Load current waveform of proposed circuit @100rpm 200mA/div

Figure 22 - Load Current Variation of TEFR [(a) & (c)] and DC Chopper Fed Controller [(b) & (d)]

Input current drawn out from AC supply by the DC chopper fed fan regulator is different from its load current, because the fan is cut off from the AC supply during part of every switching cycle. However, the input EMI filter retains the continuity of input current without letting it go to zero during these brief intervals. Thus, input current continues to follow the sinusoidal profile but with little more running-ripple. Figure 23 shows the input current waveform when the fan runs at 100 rpm, which clearly indicates the basic sinusoidal form with little increased running-ripple compared to the corresponding load current waveform in Figure 22. The input current of TEFR is also given in Figure 23 (a) for comparison and to show the point that the TEFR gives input current, which is same as the load current, have discontinuities and harmonics.



(a)
Input current waveform of traditional EFR @100rpm 200mA/div

(b)
Input current waveform of proposed circuit @100rpm 100mA/div

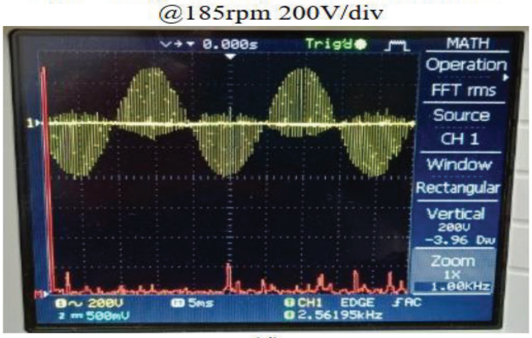
Figure 23 - Input Current Waveforms at 100 rpm (a) TEFR (b) DC Chopper Fed Controller

Figure 24 shows the voltage waveforms applied to the fan by the proposed fan regulator and the TEFR together with corresponding harmonic spectra at fan speeds of 100 rpm and 185 rpm. It clearly shows that the proposed FR applies near sinusoidal voltage with minimal content of low order harmonics, whereas the TEFR applies a highly distorted voltage with significant amount of lower order harmonics. Voltage waveform due to the TEFR shows some deviations over its simulated waveform and this is mainly due to the LC ringing and triac reverse recovery.

(a)
Load voltage waveform of traditional EFR @100rpm 200V/div

(b)
Load voltage waveform of proposed circuit @100rpm 200V/div

(c)
Load voltage waveform of Traditional EFR @185rpm 200V/div



(d)
Load voltage waveform of proposed circuit @185rpm 200V/div

Figure 24 - Load Voltage Variation and FFT Analysis of TEFR (a) & (c) and DC Chopper Fed Controller (b) & (d)

5. Conclusions

The aim of this study was to develop an affordable electronic fan regulator with reduced harmonics and ripple free speed. After simulating different alternative methods, DC chopper fed controller was found to be the most viable solution. Compared to TEFR, it was proved that the proposed method can feed current continuously to the fan and achieve ripple free speed. Also, near sinusoidal current waveforms suggest lesser current harmonics and better thermal stability. Moreover, according to the results, the proposed solution successfully reduced 3rd voltage harmonic around 75% and 5th voltage harmonic around 80% compared to TEFR. Thus, the proposed fan regulator will be a better replacement to the TEFR that suffers several drawbacks. Since the proposed controller is equipped with a microcontroller, it can be easily integrated to modern smart homes as well.

References

1. Waghare, S., Tutakne, D. R., Deshmuk, A., Mardikar, M., "PWM Controlled High Power Factor Single Phase Fan Regulator", Proceedings of the Third International Conference on Electronics Communication and Aerospace Technology, Coimbatore, India, 2019, pp. 59-64, IEEE Xplore ISBN: 978-1-7281-0167-5.

2. Ambhorkar, K., Rana, A.K., Jain, P., Tutakne, D.R., "Single Phase AC-AC Converter with Improved Power Factor for Efficient Control of Fan Motors", 7th India International Conference on Power Electronics (IICPE), Nov. 2016, pp. 1-5.

3. Wijerathna, M. D. A. K., "Remote Control Hum Less Fan Controller Unit", MSc thesis, Electrical Engineering, University of Moratuwa, 2010.

4. Ba-Thunya, A. S., Khopkar, R., Wei, K., and Toliyat, H.A., "Single Phase Induction Motor Drives - A Literature Survey", IEEE International Electric Machines and Drives Conference, 2001, pp. 911 – 916.

5. Latt, A. Z., Win, N. N., "Variable Speed Drive of Single-Phase Induction Motor Using Frequency Control Method", 2009 International Conference on Education Technology and Computer, Singapore, April 2009, pp. 30-34.

6. Manias, S., "Power Electronics and Motor Drive Systems", 1st edition, Massachusetts: Academic Press, 2016, pp 183-269.

7. Young, C., Liu, C., and Liu, C., "New Inverter-Driven Design and Control Method for Two Phase Induction Motor Drives", IEE proceedings on electric power application, Vol 143, No. 6, Nov 1996, pp. 458-466.

8. Ishak, D., Tiang, T.L., Choy, S.K., "Performance Evaluation of Permanent Split Capacitor Single-Phase Induction Motor for Ceiling Fan Application", 18th International Conference on Electrical Machines and Systems (ICEMS), Thailand, Oct 25- 28, 2015., pp. 1865-1870.