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Speed control of three phase induction motor using single phase supply along with active power factor correction

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Abstract

Majority of industrial drives use electric motors, since they are controllable and readily available. In practice, most of these drives are based on ac induction motor because these motors are rugged, reliable, and relatively inexpensive. The proposed technique of single phase to three phase conversion has a wide range of applications in rural areas and also in industries where three phase equipment or motors are to be operated from the easily available single phase supply. These converters are excellent choice for situations where three phase power supply is not available. The added advantage is that the three phase motor is more efficient and economical than the single phase motor. Also the starting current in three phase motor is less severe than in single phase motor. This needs a strong, efficient cost effective and high quality single phase to three phase conversion. Advanced PWM techniques are employed to guarantee high quality output voltage with reduced harmonics and sinusoidal input current irrespective of the load. To obtain sinusoidal input current at the terminal of single phase source a high performance active input power factor correction technique for single phase boost switch mode rectifier operating with discontinuous current conduction is used. The operation is based on variable turn-on time. Equal Area Criteria (EAC) is applied to the discontinuous current operation. To obtain high quality output voltage, double edge modulated sine wave PWM technique is implemented for three phase inverter. From experimental results obtained on a laboratory prototype it can be concluded that input power factor remains nearly unity for any variations in the load or speed. Thus three phase ac drives using single phase supply with improved power factor is an approach to implement high frequency induction boosting along with the three phase PWM inverter for controlling the speed of three phase induction motor by maintaining v/f ratio at constant value. This scheme can be used in lathe machines, small cranes, lifts etc, which are frequently switched ON and OFF[1].

[1] This study has been implemented at Power Electronics Lab of VIT, University of Pune.

Keywords: *power factor correction, boost-converter, equal area criterion, Power MOSFET, PWM inverter, v/f ratio, FCT, RCT, VCT, OCT.*

1. Introduction

Power electronics is a branch of engineering which is concerned with conversion and control of electrical power for various applications. Often a conversion system is a hybrid type that mixes more than one basic conversion process. The output of an uncontrolled converter can be controlled by controlling the duty cycle of the boost switch connected at the output of converter. The switching type of conversion can introduce distortion and generate harmonics on source line and load; such problems can be eliminated by introducing filter at the input. The non-ideal character of the input current drawn by these rectifiers creates number of problems like increase in reactive power, high input current harmonics, low input power factor, lower rectifier efficiency, large input voltage distortion etc. To compensate for the higher reactive power demand by the converters at high power transfer levels, power factor correction becomes mandatory. To overcome these problems number of passive and active current wave shaping techniques [1-12] have been suggested in the literature. But the passive power factor correction techniques have the disadvantages like large size of reactive elements, power factor improvement for a narrow operating region, large output dc voltage ripple [1]. Active current wave shaping techniques overcome these disadvantages and significantly improve the performance of rectifiers. Hysteresis current control is a simple active current wave shaping technique that gives close to unity power factor operation while delivering near sinusoidal currents [2]. The rectifiers using discontinuous conduction of input current with a single boost switch gives close to unity power factor at constant turn-on time and frequency of the boost switch [3, 4]. Current control technique may use continuous conduction mode or discontinuous conduction mode. The popular continuous mode of conduction with switch mode rectifiers are hysteresis current control with constant hysteresis window, Bang bang hysteresis current control and constant switching frequency current control with error triangulation [5-7]. Discontinuous mode of conduction operates with constant switching frequency and variable turn-on time using one or two switches [8,9]. Several dedicated power factor controller integrated circuits such as Microlinear's $ML4812$ [10] and Unitrode $UC2854$ [11] are currently available. Application of equal area criterion (EAC) to discontinuous current operation improves the power factor to nearly unity [12]. Zheren Lai [13] proposed a family of constant switching frequency PWM controllers for power factor correction that uses continuous conduction mode. P. M. Patil proposed a method for single-phase to three-phase conversion using sinusoidal PWM [14].

The proposed topology employs a boost converter to boost the dc link voltage to 325 V using boost switch mode rectifier. The application of EAC gives an approximate relation by which a correction can be established between desired input fundamental current (hence power) and the turn-on time (variable) of the boost switch. In EAC it should yield the same area for the discontinuous current pulse as that of the area under reference input current in every switching period. Thus the criterion yields greater accuracy for single-phase rectifiers since it has freedom to vary the turn-on time [8]. The dc link voltage is fed to three phase PWM inverter. PWM inverter reduces the harmonic content to larger extent. Changing the modulation index can easily vary the output voltage of inverter. IC HEF4752 V is a special purpose IC which can be used to control the speed of three phase ac motor by maintaining v/f to constant value [16-18].

The remainder of the paper is organized as follows: Section (2) focuses on the system overview. Section (3) emphasizes on background concerning the EAC. Section (4) describes the implemented scheme (hardware and software) along with its design details. Section (5) compares various experimental results. Section (6) presents some conclusions along with future issues that need to be addressed.

2. System overview

The block schematic of implemented speed control of three phase induction motor using single phase supply along with active power factor improvement is as shown in Fig 1. The block diagram can be divided into two parts. Part 1 consists of an input filter, a boost inductor, a single-phase diode rectifier, an active power factor correction stage using the principle of equal area criteria along with its firing scheme and a dc link filter capacitor. Number of switches may be increased depending on the power to be handled by the converter. The active wave shaping of the input current waveforms is obtained through L_2, S and D_5 as shown in Fig 3. The boost switch S is turned ON at constant frequency with variable ON time. The duty cycle of S is varied for load variations such that the input current is always discontinuous. Consequently the input current begins simultaneously to increase at a rate proportional to the instantaneous value of the phase voltage. Moreover the specific peak current value during each ON interval is proportional to the average value of the input phase voltage during the same ON interval. Since the average value of voltage varies sinusoidally, the input current peak also varies sinusoidally. Moreover, since the current pulses always being at zero it means that their average values also vary sinusoidally. Consequently the input ac current consist of the fundamental component and a band of high frequency unwanted components centered around the switching frequency of the boost switch. Since this switching frequency is usually very high (kHz), filtering of the unwanted input current harmonics becomes a relatively easy task and can be achieved with the help of a small input capacitor C_1 and inductor L_1. Therefore the overall input power factor after filtering (i.e. at ac source) is very close to unity. Part 2 represents three phase voltage source PWM inverter with motor load. Transistors are being used as switching devices along with anti-parallel diodes. The boosted dc voltage is connected to three phase induction motor through a three phase bridge inverter with a suitable control circuitry which changes the switching frequency of inverter from 0 to 1 kHz which leads to the control of the frequency of the output of inverter from 0 to 72 Hz. For continuously variable speed control, the output frequency of inverter must be varied. The applied voltage to the motor must also be varied in linear proportion to the supply frequency to maintain constant motor flux. At low frequency, where the motor inductive reactance is low, boosted voltage is used to compensate for the stator IR voltage drop. Thus control of both voltage and frequency is necessary for proper variable speed operation [16]. To generate PWM signal, a special purpose IC HEF4752V manufactured by Phillips is used. In this IC, principle of double edge modulation of carrier wave is achieved as shown in Fig 4. Each edge of carrier wave is modulated by variable time δ, where δ is proportional to $\sin\alpha$ and α is the angular displacement of the unmodulated edge. The modulation of the output waveform is achieved by opening and closing the upper and lower switching element in each phase of the inverter. Closing the upper element gives a high output voltage, and closing the lower element gives low output voltage.

3. Equal Area Criterion

The boost switch S (See Fig 3) is operated at constant switching frequency such that the rectifier input current is discontinuous in nature as shown in Fig 2(a). A typical input current pulse super imposed on the reference current $I_m Sin\omega t$ is shown in Fig 2(b). The instantaneous current $i(t)$ in ON mode of the boost switch (storing the energy in the boost inductor L_2) is given by,

$$i(t) = I_1 + \frac{E_{m2}}{\omega L_2}\left[\cos\alpha - \cos(\alpha + \omega t)\right] \quad for\ 0 \le \omega t \le \omega t_{on} \quad (1)$$

and $i(t)$ in OFF mode (discharging the stored energy in the boost inductor into output capacitor bank C_2 and load) is given by,

$$i(t) = I_2 + \frac{E_{m2}}{\omega L_2}\left[\cos(\alpha + \omega t_{on}) - \cos(\alpha + \omega t_{on} + \omega t)\right] - \frac{V_{dc}}{\omega L_2}\omega t \quad (2)$$

$$for\ 0 \le \omega t \le \omega t_{off}$$

where,

I_1/I_2	initial value of current in on mode / off mode
f	supply frequency
$\omega = 2\pi f$	angular frequency (rad / sec)
ωt	incremental angle
L_2	value of boost inductor
E_2	rms voltage across input filter Capacitor C_1.

In EAC, the area under the triangle (A_1), which depends on the peak value of the current (I_2) and the pulse area (A_2) are equated.

4. Implemented Scheme

The detailed circuit diagram of boost switch mode rectifier is as shown in Fig 3. Driving pulses for switch S are generated through PC. The duty cycle and ON time of these pluses are calculated through software when user enters the input voltage value. These pluses are outputted on one of the outputs of the printer port. This signal with respect to ground is collected from the printer port and passed through an opto-isolator and a MOSFET driver IC and connected at the gate to source of the MOSFET switch S . The necessary flow chart for the required software is shown in Fig 6. The output DC voltage selected should be more than the critical voltage that allows rectifier input current to fall to zero at the end of each switching period. The critical value of the output DC voltage can be calculated by solving equations (1) and (2) for $\alpha = 90°$, giving duty cycle D as,

$$D = \frac{V_{dc} - E_{m2}}{V_{dc}} \quad (3)$$

where,

$$D = \frac{t_{on}}{t_{on} + t_{off} + t_d} \quad (4)$$

The value of L_2 can be selected in such a way that the input current during OFF time should reach to zero value. Thus L_2 is a function of switching frequency, output dc voltage and input supply voltage and given by,

$$L_2 = \frac{E_{m2}}{2\omega I_m}\left[D + \frac{E_{m2}}{2V_{dc}}\right]^2 \quad (5)$$

Supply input filter inductor L_1 , filter capacitor C_1 and output dc filter capacitor C_2 are selected using,

$$C_2 = \frac{100\, I_{f_b(peak)}(1-D)}{\sqrt{2}\ \%ripple(f_b)\omega V_m} \quad (6)$$

where,

$I_{fb(peak)}$	amplitude of f_b^{th} harmonic component of current I
D	duty-cycle
f_b	switching frequency
V_m	peak value of input phase voltage

$$\frac{X_{L_1}}{X_{C_1}} = \frac{1}{(f_b - 1)^2}\left[\frac{I_{C_1(f_b-1)}}{I_{L_1(f_b-1)}} + 1\right] \quad (7)$$

where,

X_{L_1} and X_{C_1}	reactance of L_1 and C_1 at Fundamental frequencies,
$I_{L1(f_b-1)}$ and $I_{C1(f_b-1)}$	amplitudes of $(f_b - 1)^{th}$ harmonic component of currents I_{L_1} and I_{C_1}.

Evaluation of (7) reveals that size of the filter components is a function of the boost switch switching frequency (f_b). The size of the filter components become smaller and smaller for higher switching frequency (f_b). Consequently all the harmonics of the input current becomes smaller and smaller and the input power factor is nearly unity.

Part 2 of the block diagram represents the voltage source PWM inverter. The basic function of PWM IC HEF4752V is to provide three complementary pair of output drive waveforms which, when applied to the six element inverter, open and close the switching element in the appropriate sequence to produce a symmetrical three phase output. In our case BU508A power transistor is chosen as switching element of the inverter. The drive waveforms are applied to upper three transistors of inverter with isolation. The integrated circuit is completely digital, so that the repetition frequency of PWM signal is always an exact multiple of the inverter output frequency. This results in excellent phase and voltage balance and consequent low motor losses. To improve the pulse distribution at lower motor speed the switching frequency is derived from the higher multiples of inverter output frequency. A hysterisis between the switching point is included to avoid jitter when operating in these regions [18].

The PWM inverter along with control circuit using HEF4752V is as shown in Fig 5. The four clock inputs FCT, RCT, OCT and VCT are supplied from NE 566 VCO and Hex schmitt trigger IC 74C14. The clock input FCT controls the inverter output frequency (F_{out}) hence the motor speed. The clock frequency of FCT is related to output frequency of inverter [18] as

$$F_{FCT} = 3360 \times F_{out} \quad (8)$$

The output frequency of the inverter can be controlled from 0 to 72 Hz by varying frequency of FCT.

In case of induction motor, in order to maintain constant motor flux, the voltage-time product must be kept constant. The IC automatically satisfies this requirement by making the output voltage directly proportional to the output frequency. The level of the average inverter output voltage at given output frequency is controlled by the VCT clock input. The change in the output voltage is achieved by varying the modulation depth of the carrier. Increasing F_{VCT} reduces the modulation depth and hence the output voltage, while decreasing F_{VCT} has the opposite effect. The relation between F_{VCT} and F_{OUT} is given by Starr and Loon [17].

$$F_{VCT(nom)} = 6720 \times F_{out(\max)} \quad (9)$$

With F_{VCT} fixed at $F_{VCT(nom)}$, the output voltage will be linear function of the output frequency upto $F_{out(\max)}$. However, at low frequencies, IR loss compensation changes F_{VCT} varying this linear relationship. VCT has been designed as a fixed oscillator and sacrificed for a certain percentage of torque at low frequencies, i.e. IR compensation is ignored at lower frequencies.

The reference clock input RCT is a fixed clock used to set the maximum inverter switching frequency $f_{s(\max)}$. The clock frequency F_{RCT} is related to $f_{s(\max)}$ [17] as,

$$F_{RCT} = 280 \times F_{s(\max)} \quad (10)$$

The absolute minimum value of the inverter switching frequency $f_{s(\min)}$ is set by the IC at $0.6 \times f_{s(\max)}$. These figures apply only if FCT is within the range $0.043 \times F_{RCT}$ to $0.8 \times F_{RCT}$ and F_{FCT}/F_{VCT} is less than 0.5. The output delay clock OCT, operating in conjunction with the data input K is used to set the inter-lock delay period which is required at the change over between the complementary output at each phase. When K is high it keeps the jitter caused by lack of synchronization between FCT and OCT to a minimum. With K high the inter-lock delay period [17] is given by $16/F_{OCT}$ ms, where F_{OCT} is in kHz.

The data input I determine whether the inverter used is thyristorised or transistorised. The input I low corresponds to transistor mode and I high corresponds to the thyristor mode. Here input I is low. In the transistor mode, with data input L low, indicates all main and commutation signal inhibited and with L high, the normal modulated block pulses continue. The action of L inhibit the output circuit only i.e. when L is low the internal circuit generating the output signal continue to operate but only the output is disabled. The data input CW gives the facility of the direction .reversal. When the input CW is high, the phase sequence is R, Y, B and when low it become R, B, Y . The three data input A, B, C are provided for use during the production testing. During normal operation they must be grounded. The IC HEF4752V has 12 outputs, out of which 6 outputs have been used and these outputs are connected to the base of power transistors BU508A for implementing inverter bridge.

5. Results and Discussion

The performance evaluation of the single-phase to three phase conversion with active power factor correction is done with input voltage of 85V (rms), gate drive pulses of frequency 20kHz with duty cycle kept at 68% to get an output dc voltage of 325V. The proto-type of the scheme is built for experimental purpose. Selected results are given in Fig 7. Fig 7(a) and 7(b) shows the input voltage and current waveforms before and after power factor correction. For the same voltage waveform if power factor is not corrected, the current waveform is non-sinusoidal and not in phase with the applied voltage. Hence the power drawn for the same load demand is more. But after correcting the power factor the current waveform becomes pure sinusoidal and in phase with the input voltage. Fig 7(c) shows discontinuous rectifier input current I_2, Fig 7(d) represents input current I_1 and rectifier output voltage V_{rect}.

PWM pulses for driving boost switch 'S' are generated through PC whose duty cycle is calculated through software using the values of input and output voltages. During on period of the switch the input current through L_2 rises at a rate determined by the input source voltage V_{in} and inductor L_2. During off period of the switch the current through the inductor L_2 decreases at a rate determined by input voltage V_{in}, output dc voltage and inductor L_2. Since each of these voltage average values carries sinusoidally, the input current peaks also vary sinusoidally. Moreover since the current pulses always begin at zero, it means that their average values also vary sinusoidally. Consequently the input ac current consists of the fundamental component and a band of high frequency unwanted components centered around the switching frequency of the boost switch. Since this frequency can be in the order of several tens of kHz, filtering out the unwanted input current harmonic becomes a relatively easy task. It is also seen that input power control (or output voltage regulation) can be achieved through pulse width modulation of the boost switch.

Finally under the operating conditions described here, the displacement input power factor before filtering is unity. Consequently, the overall input power factor (before filtering) becomes equal to harmonic input power factor. It is noted that the current harmonics associated with this power factor can be suppressed by a relatively small input capacitance C_1 and inductor L_2 because of their frequencies. Therefore the overall input power factor after filtering (i.e. at the ac source) is very close to unity.

The testing of inverter was carried out at a dc link voltage of 325 V. A PWM inverter was designed and tested whose switching frequency was selected as 1 kHz. Fig. 7(e) shows the PWM control signal to the base of inverter switching transistors. A PWM inverter along with the high frequency boost converter was tested for various load conditions by loading the motor. The induction motor used was a three phase, 440 V, 0.75 A, 0.5 HP, 1440 RPM type. The motor was also tested for variable voltage and variable frequency condition to have v/f control and the system was found working satisfactorily. For a constant dc link voltage, with variation of reference controller FCT, motor terminal voltage and speed can be varied.

Fig 7(f) shows the output voltage of PWM inverter whereas Fig 7(g) and Fig 7(h) shows the expanded version of line voltages RY & YB, and expanded version of line to line voltages RY & BR of the three-phase bridge inverter respectively. Waveforms are phase shifted by 120 degree with each other. The nature of waveform is sine weighted PWM which fully satisfies the magnitude and phase balance. Use of PWM control has the advantage of reduction in harmonics in the output voltage waveform, hence the reduction in heating of motor compared to the 6-step square wave inverter. PWM technique also reduces pulsating torque of the motor.

Motor line current is nearly sinusoidal in nature, which fully satisfies the design requirement. With the increase of switching frequency the motor line current can be made more sinusoidal. At an increased load a small distortion is observed in the PWM output voltage waveform. This distortion can be filtered out using appropriate filter.

6. Conclusion

Application of EAC for discontinuous current operation for single-phase boost rectifier with variable ON time reduces the lower order harmonics. The higher order harmonics around the lock-up frequency can be easily filtered out with a suitable input filter. The higher switching frequency operation reduces this filtering requirement. Also, high power application is possible because of operation at high switching frequencies. The EAC criterion yields the following advantages while operating with discontinuous current conduction:-

1. Linear relation between reference and actual current.
2. Power factor is close to unity even at low switching frequencies.
3. Harmonics ratio with respect to fundamental remains almost constant at all load conditions.
4. Simple closed-loop control system is possible to realize.

The line to line voltage of three-phase bridge inverter is phase shifted by 120 degree with each other and the nature of waveform is sine weighted PWM which fully satisfies the magnitude and phase balance. Use of PWM control has the advantage of reduction in harmonics in the output voltage waveform, hence the reduction in heating of motor. PWM technique also reduces pulsating torque of the motor. Motor line current is nearly sinusoidal in nature. By increasing the switching frequency the motor line current can be made more sinusoidal. With increase in load a small distortion is observed in the PWM output voltage waveform, which can be filtered out using appropriate filter. It was observed that the mains current drawn by the system is nearly sinusoidal and operating at nearly unity power factor.

A further refinement in the results to make power factor exactly unity/ leading is the subject of future work.

7. Acknowledgements

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8. References

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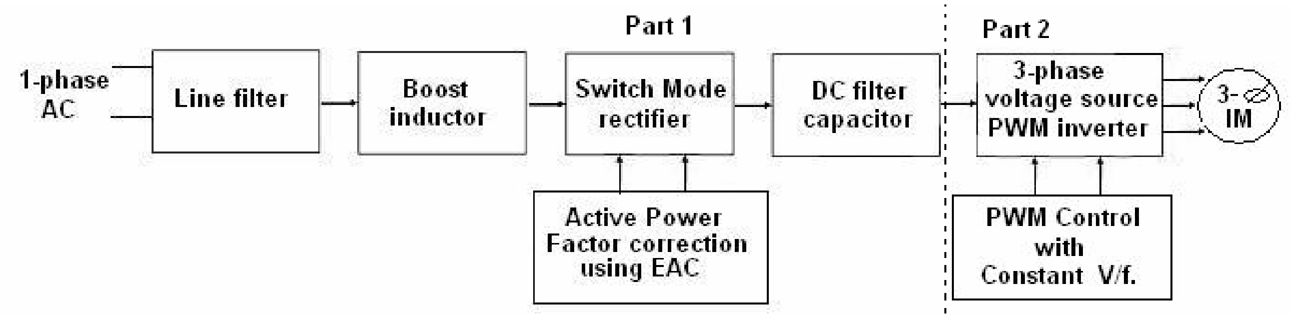
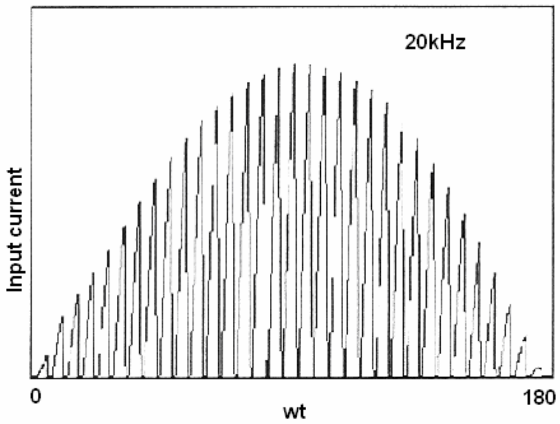


Fig. 1 Block schematic of implemented scheme



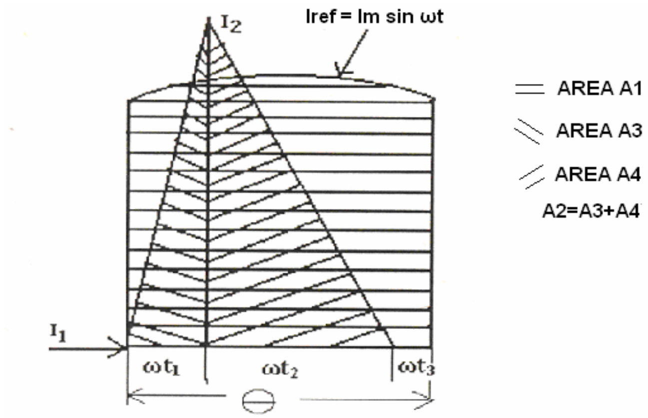


Fig. 2 (a) Discontinuous rectifier input current **(b) Input current pulse super imposed on the reference current**

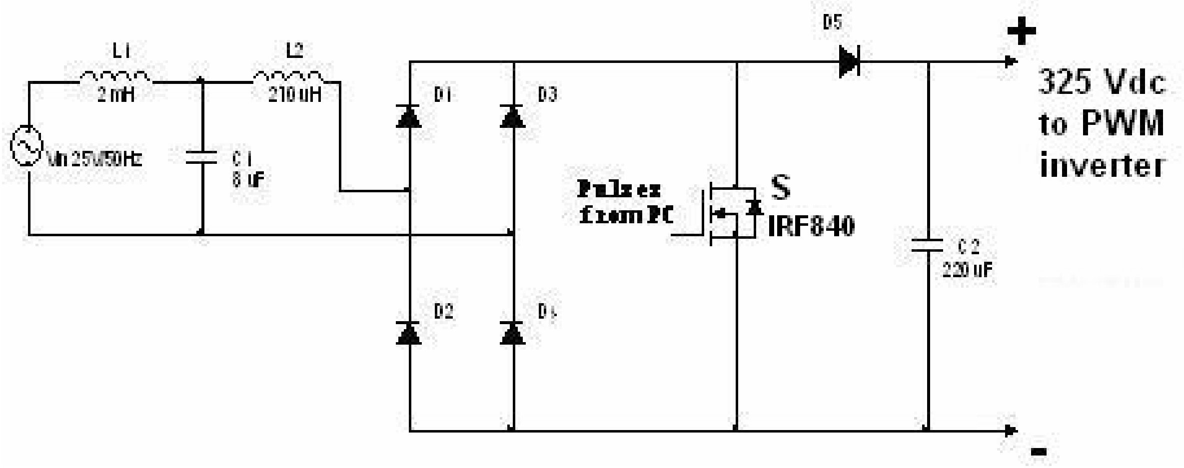


Fig. 3 Circuit diagram of Switch mode Rectifier

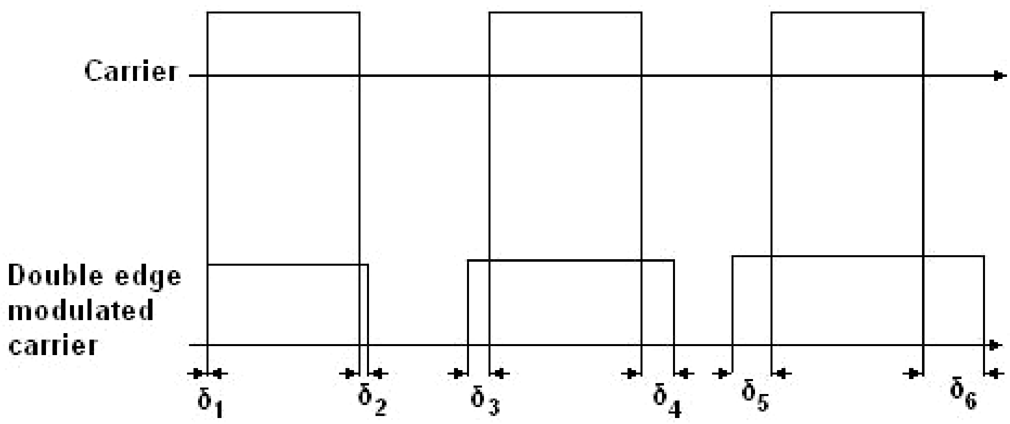


Fig. 4 Detail of double edge modulation.

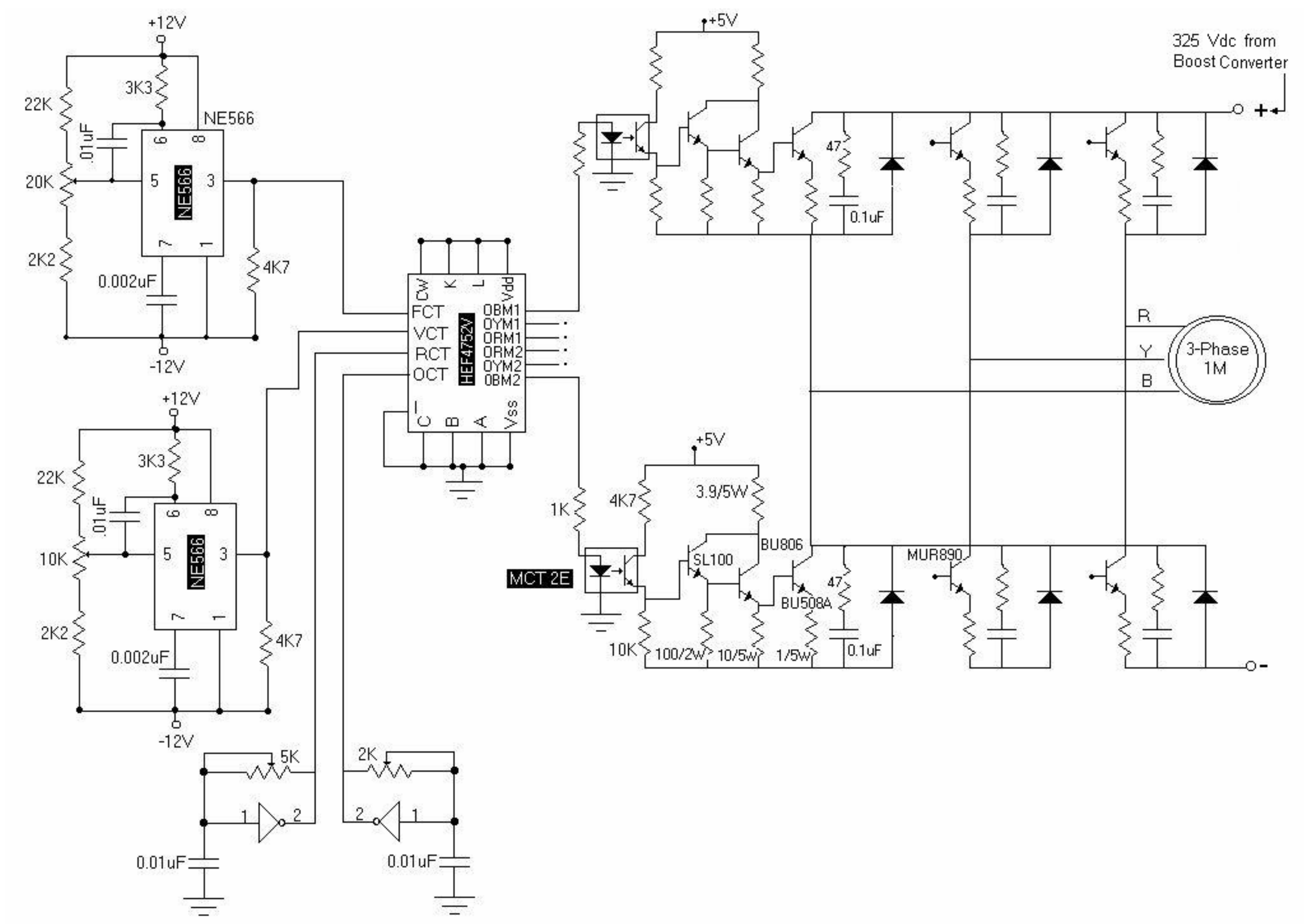


Fig. 5 Three phase PWM inverter with control circuit

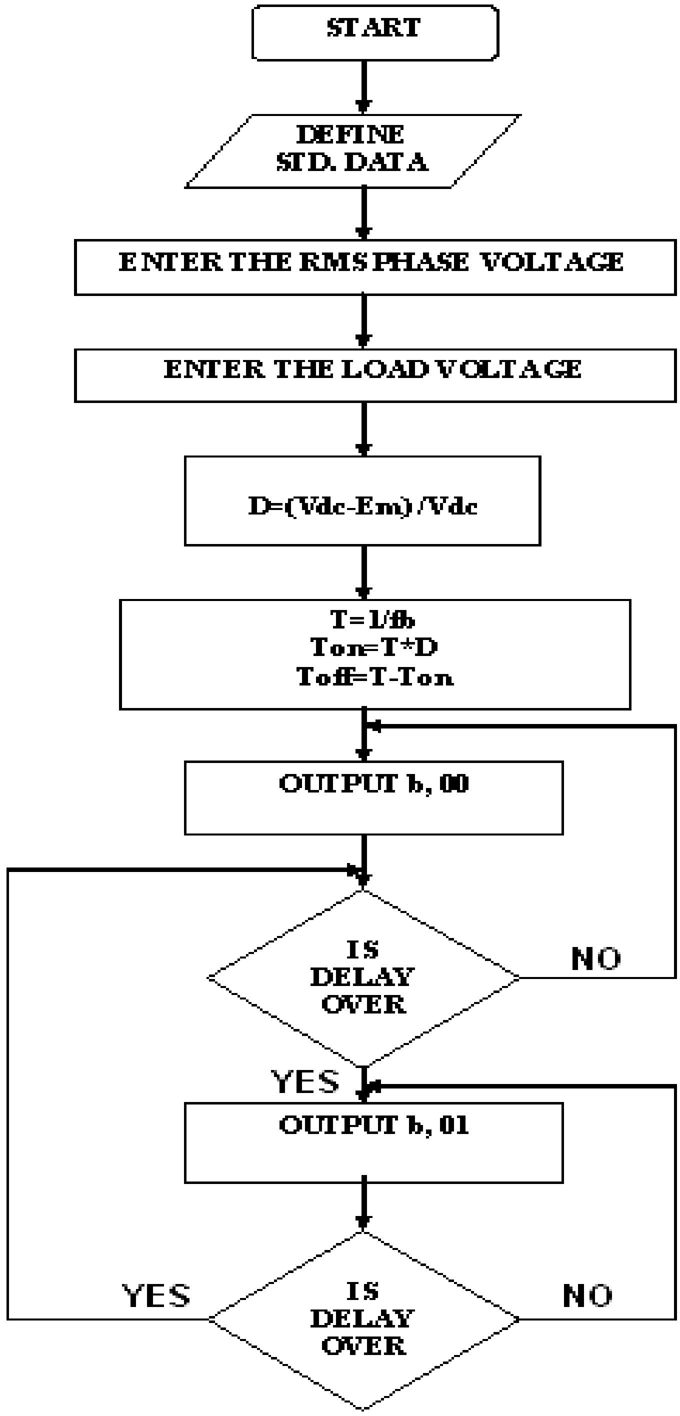


Fig. 6 Flow chart

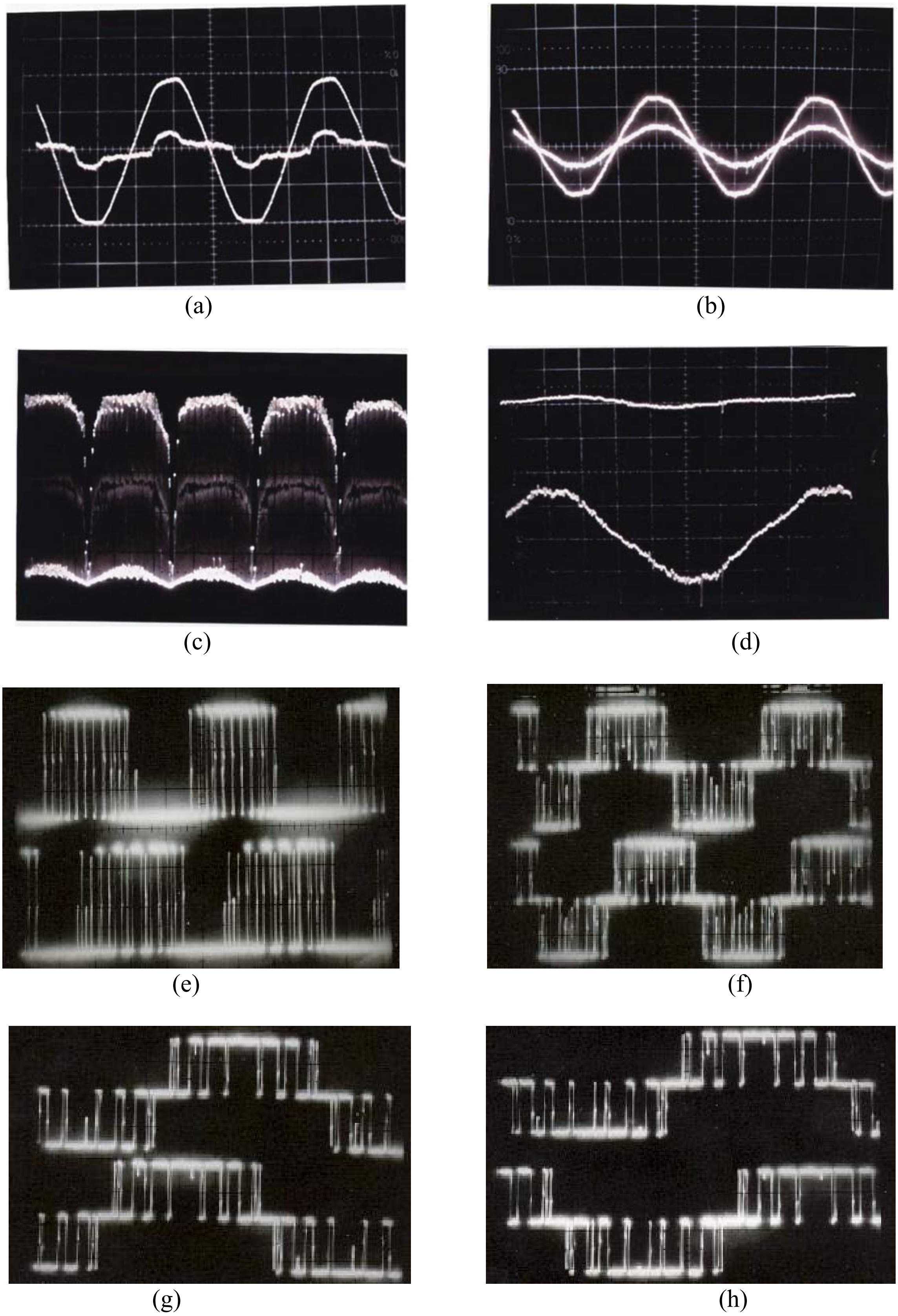


Fig. 7: Photographs at different test points: (a) Input voltage V_{in} & Input current I_1 without power factor improvement, (b) Input voltage V_{in} & Input current I_1 with power factor improvement, (c) Discontinuous rectifier input current I_2, (d) Input current I_1 & Rectifier output voltage V_{rect}, (e) firing pulses for PWM inverter, (f) Output voltage of PWM inverter, (g) expanded version of line voltages RY & YB, (h) expanded version of line voltages RY & BR.

9. Author Biographies

Pradeep Mitharam Patil was born in Bhusawal, District Jalgaon, Maharashtra, India on December 13,

1966. He received B. E. (Electronics) degree in 1988 from Amravati University, Amravati, India and M. E. (Electronics) degree in 1992 from Marathwada University, Aurangabad, India. From 1988 to 2002 he worked as Lecturer and Assistant Professor in Electronics department at various engineering colleges in Pune University, India. He received the Ph.D. degree in Electronics and Computer Engineering in 2004 at Swami Ramanand Teerth Marathwada University. He is member of various professional bodies like IE, ISTE, IEEE and Fellow of IETE. Presently he is working as Professor of Electronics Department at Vishwakarma Institute of Technology, Pune, India. His research areas include pattern recognition, fuzzy neural networks and power electronics. His work has been published in various international and national journals and conferences including IEEE.

Sanjay Laxmanrao Kurkute was born in Loni Dist Ahmednagar, Maharashtra, India on December 13,

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