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Fig. 26. Test the system on lighting a 100w lamp

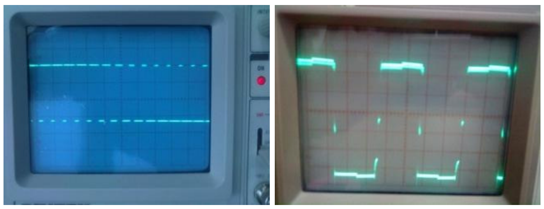


Fig. 27. Bidirectional SPWM

In the next step, the inverter is applied to the motor terminals as shown in fig. 28.

In Fig. 28, the systems configuration with encoder is shown. To monitor the speed of the machine, the output pulses from encoder are transferred to the processor (it is an ATmega 8bit from AVR family microcontrollers). Then using a USB module and USART series communication algorithm the sample of the speed are transferred into a computer. Using MATLAB software, the received data are saved into a matrix and the samples are plot using MATLAB plotting toolbox. It is important to mention that the number of samples per seconds (40 samples per seconds) are not high enough to reach continues plot for the speed. Fig. 29 (a), has depicted the speed versus time characteristic of the machine in practice.

In Fig. 29 (b), the current of the machine at the input terminal of the machine is shown. For this figure the volt/Div of the oscilloscope is set to 5volt.

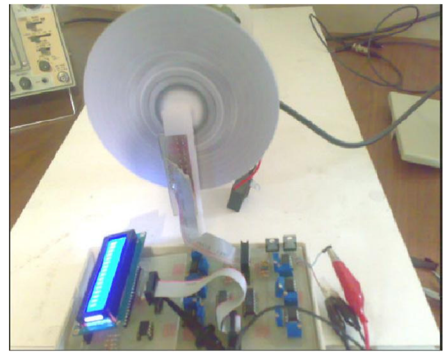
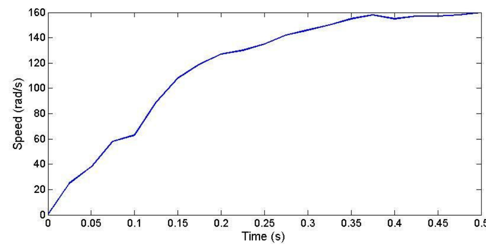
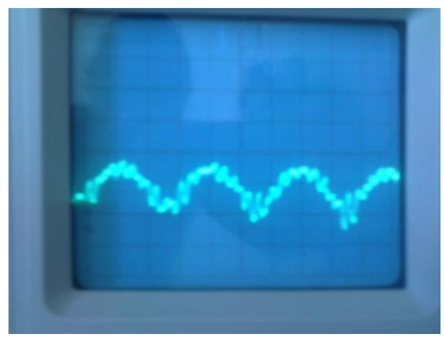


Fig. 28. Bidirectional SPWM



(a)



(b)

Fig.29. (a): Practical result of the speed versus time of the machine. (b): Machine current at specified reference speed

7. Conclusions

The main purpose of this paper is the practical consideration for implementing a PCSPIM driver. One of the main aspects of this paper is dealing with the practical issues which exist in the implementation level. The designed drive system can find its application in home appliance where, there is no need to a complex control system. Open loop control method based on the V/f constant approach is used to control the speed of the motor in a specific value. Practical results show the effectiveness of the drive system for easy speed control of a PCSPIM.

Boot-strap technique is more economical than the first approach which uses separate transformers for each leg.

1.5. Protection circuit: For a drive system the most important concern is the currents that are flowing through the system's components. In normal operation of the system, there is no concern if the system is designed correctly. But for abnormal conditions, for example when a short circuit occurs, the system will be damaged unless a protection system protects the system. In this study, a small high power resistor is put in each MOSFET legs to sense the current which is flowing through the MOSFETs and shut down the system in abnormal situations such as shaft lock, huge load, and other abnormal conditions.

Another protection system like discharging resistor bank for DC-link filter capacitor has been discussed in previous sections.

The complete circuit of the designed inverter is shown in Fig. 23.

2. Printed Circuit Board (PCB) design: By using Protel DXP software, the circuit's PCB is designed.

Several practical assumptions are considered. Firstly, Logic system's ground and power ground are separated and finally at a single point they are connected together via an inductor. Since DC-link section of the system is a high voltage part, the tracks which are connecting different components in this section should be as short and direct as possible. Otherwise the tracks make a great capacitance which is not acceptable and causes problems in normal operating of the system. Track's widths are selected based on the current that may flow through them. In this study the tracks for connecting the logic components are 0.3 mm in width, for drive circuit the width is 1 mm and for the high voltage components the tracks are 3 mm in width.

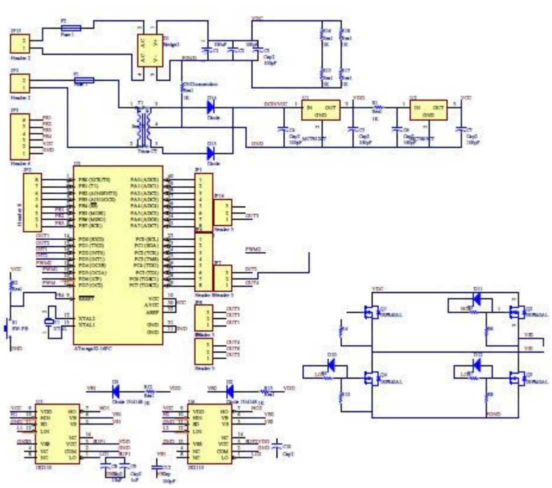


Fig. 23. The complete circuit

The other important feature that is needed to be considered is the grounding of the circuit. Current in all elements finally will flow to the ground of the system which means that the ground should be strong enough. On the other hand, inductive currents always are willing to minimize the flowing path. These currents also make the tracks inductive. Thereby, widening the system ground is needed due to huge amount of ground current and to minimize the inductive impedance of the tracks. In this study, the polygon feature is used to widen the ground system.

3. Rate limiter: Rate limiter is needed to ensure the slip change within allowable range (e.g. rated value) and it should be considered in the main block diagram for safety as shown in Fig. 24. Fig. 25 represents the case, when no rate limiter is used.

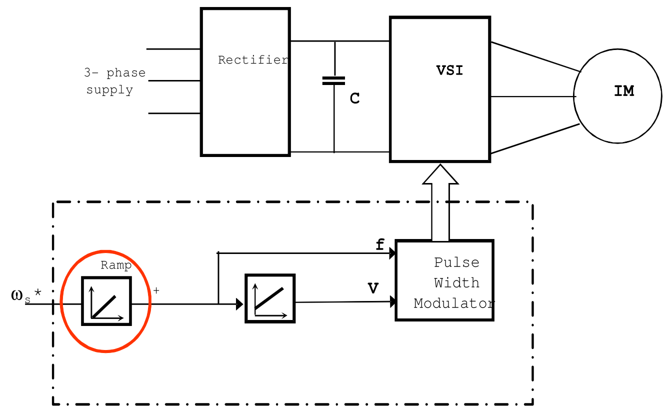


Fig. 24. Block diagram of open-loop control approach with rate limit

6. Practical Results

The first thing before connecting the inverter to the motor is to check that the inverter works correctly. For this purpose the inverter is programmed to generate 220V, 50Hz AC output voltage and it is applied to a lamp. No flicker or blinding is detected that shows that the output voltage is sufficiently out of harmonics and it is working properly. Fig. 26 shows the inverter while it is supplying a 100W florescent lamp

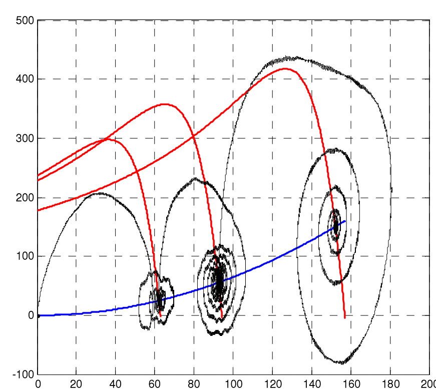


Fig. 25. With almost no rate limiter

The next step to check whether the inverter is working correctly or not is to check the output SPWM waveform. Fig. 27 shows the output SPWM signals which will be supplied to the motor.

1.2. Processing unit: To design a system economically, selecting the proper elements plays the most important role. The processors cost is too much comparing to other elements used in the circuit and they should be selected to have capabilities which are according to their tasks. For our purpose the processor is responsible for:

a) Receiving the decoder sensors' signals and computing the shaft's position and speed.

b) Computing the required voltage amplitude and frequency based on the desirable speed.

c) Generating the SPWM signals for applying to the inverter switches drive circuit.

SPWM signals are generated using a lookup table of 21 samples (mf=21) of a 50Hz sinusoidal waveform and a timer counter block diagram. Since a lookup table is used, generating the SPWM signals wouldn't take many cycles. Other tasks also do not need a great number of computation cycles. Thus the only limitation for choosing a suitable processor is the number of timer/counter blocks in the processor that is needed to generate the unidirectional SPWM signal for the full-bridge switches.

In this paper, a micro-controller from ATMEL-AVR family - more specifically ATMega 8 - is proper to perform the aforementioned tasks.

1.3. Power switches: For any application, the proper switch should be selected based on the characteristic of the circuit such as VA rating, and switching frequency. Fig. 21 shows a comparison between different power switches and their application ranges.

For our purpose which is a 100W inverter, the best choice is using the power MOSFETs. The MOSFETs are needed to be able to tolerate at least 2 Amperes and 500V. It is important to mention that the switching inverters contain voltage spikes up to twice the DC-Link voltage. Therefore, the MOSFETs should be able to tolerate 500V. In this study, MOSFETS from International Rectify Company and IRFXXX family is used. The final circuit for inverter power switches and legs is shown in Fig. 22.

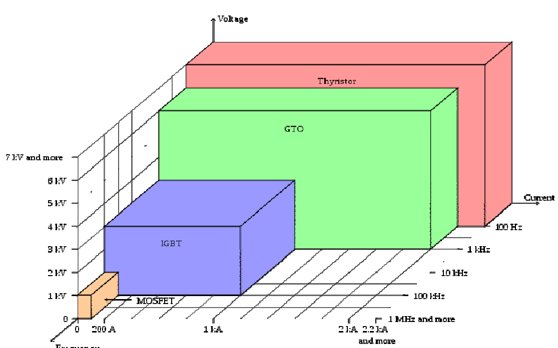


Fig. 21. Power switch comparison

A practical issue in driving power switches is the fact that power switching devices are not ideal in practice. One aspect of this non-ideal characteristic is their turning on, and turning off delay times. Most of the switching devices have a turning off delay time more than the turning on delay. This causes problems for the legs, if the turning off pulse of a switch comes at the same time as turning on pulse of the other switch, the difference between two delays causes a short circuit on DC part of the system for some instant of time. For this reason, always based on the characteristic parameters of the switching devices we need a pulse delay for the switch needed to be turned on. This delay can be implemented by a simple RC circuit that the capacitor charges with a specified time constants and discharges with another different time constant. Another way is that the processor is responsible to make a delay for sending turning on and turning off signals to the switches in a leg. This delay time is called dead-time.

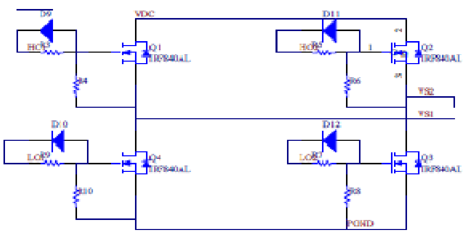


Fig. 22. The final full bridge circuit

For each MOSFET two resistors and one diode are considered. The resistors in series with MOSFET's gates are used to help the processor to make delay in turning on the switches. Also this resistor reduces the dv/dt on gate-source capacitor of the switches and is about 1-10 ohms. These resistors are by-passed by the diodes in turning off process to decrease the resistance and increase the de-charging process of G-S capacitors and hence decrease turning off delay. It is important to note that the diode should be ultra-fast. The other resistor, in parallel with G-S capacitor, is used to de-charge the unwanted charges on the G-S capacitor while the switch is off and therefore preventing the undesirable turning on of the switches. It is about 1 Kilo ohm and should be designed based on the period which the switches are off, and the value of G-S capacitor.

1.4. MOSFET driving circuit: Usually MOSFETs can be driven just by applying 15-20V to their gates. The common problem in an inverter and generally when the circuit contains power switch legs is this issue that the upper switches are float in one side and the voltage should be applied to gate with respect to the source on the other side. Different methods can be used to drive the upper switches. The simplest form is to make separate power supplies to drive the upper switches. This method is costly but it is really simple to implement. Other methods use different techniques to drive the upper switches. One method is called boot-strap method. In this method, a capacitor is charged by the system's main power supply while the bottom switch is on.

As the bottom switch gets off, the capacitor will be float and it will be connected to the upper switch and turns it on. International Rectifier Company has introduced integrated circuits (ICs) to drive the power switch legs using boot-strap technique. In this paper, IR21XX family is used as power switch legs drivers.

For this purpose, a simple full-bridge rectifying system can be used to create the proper DC-link. But the filter capacitor should be design in a way to obtain the output DC voltage with acceptable ripple. It should be noted that the DC-Link voltage ripple causes huge harmonics on inverter’s AC output voltage. Also, the DC-Link needs a protection system to prevent electric shock which de-charges the filter capacitor as the operator turns the system off, and prevent damages to capacitor as it is being energized.

The inverter is designed to drive a 100W induction motor. So the dc-link voltage is about 300VDC. Since the starting current of induction motor is very important in designing procedure of the inverter, it is assumed that the output current is about 2 Amperes.

With 10% ripple for the output voltage, the filter capacitor can be calculated as follow [19]:

$$I = C\frac{\Delta V}{\Delta t} \Rightarrow 2 = C\frac{0.1*300}{10ms} \Rightarrow C = 600\mu F \qquad (3)$$

Obviously, this capacitor is applicable just in those drive systems without control system. For Drive system with control loops it should be considered that the capacitor should be as small as possible. In practice, for control systems, a big capacitor causes the control system to face with several problems. Therefore a small capacitor should be used as DC link capacitor.

To supply the processor, logic circuit, and drive system, ±20VDC and ±5VDC are also required. Using transformers and voltage regulators (78XX and 79XX), these voltages can be obtained easily.

The final designed circuit for the DC-Link is shown in Fig. 20. As shown in Fig. 20, a relay is used to change the capacitor’s charging and de-charging path. It works in a way that during operation, an inductor is placed in the path to reduce the dv/dt rate on the capacitor, and as the system shuts down the capacitor get de-charged by a resistor bank.

In the circuit diagram two other capacitors can also be seen. These capacitors are provided to cancel out the inductance of the tracks on the Printed Circuit Board (PCB). These capacitors have low capacities and are from MKT, Polyester, or etcetera type capacitors.

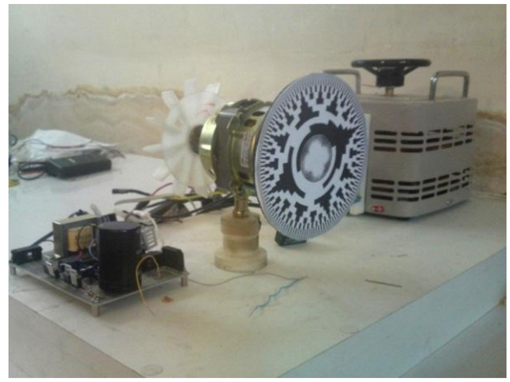


Fig. 18. The overall practical setup

Fig. 19. The implemented inverter

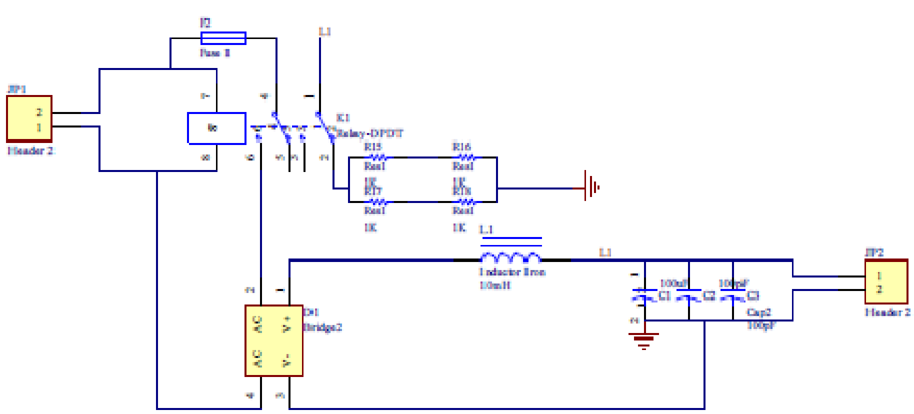


Fig. 20. The voltage supply circuit

The acceleration and speed characteristic is presented in Fig. 14.

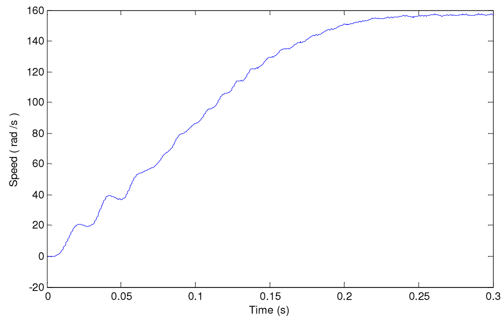


Fig. 14. Acceleration and speed characteristic

5. System Implementation

In this section, the procedures due to realizing the desired system are studied.

5.1. Overall System

A conventional drive system contains several parts including, power supply, power management system, sensing system, control system, and loads. In this paper, a power management system is designed to start up and control the speed of a PCSPIM. The main part of a power management system including rectifier, full-bridge inverter and driver is shown in Fig. 15.

Three phase 12-pulse bridge rectifier usually is used for supplying the DC-link of the system [13]. The full bridge inverter uses two power switch legs and SPWM is used to drive the legs in a way that a variable frequency, variable amplitude AC output voltage is produced. The MOSFETs are used as power switch due to the system frequency and rated power. In Fig. 16 the switching bridge is depicted.

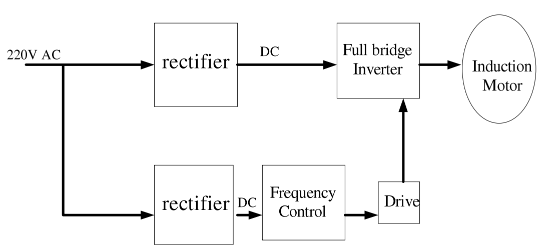


Fig. 15. Different parts of a power management system

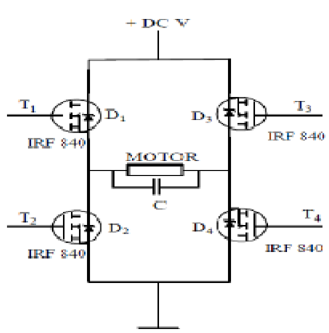


Fig. 16. MOSFET legs of a full bridge inverter

5.2. Speed Measurement

Different methods can be used to determine or measure the actual speed of the motor [14]-[20]. Encoder/Decoder systems usually are used in scalar controls of motors [15]-[18].

Here, a 10 bit encoder/decoder complex is designed and used to measure the motor speed for checking the performance of control method. This signal can be used to close the controlling loop too. Fig. 17 depicts the designed encoder which is coded using the gray coding approach.

Ten light emission diodes (LEDs) are used to read the codes and generate pulses which are compiled to measure the actual speed and position of the shaft of the motor [11]. It is needed to be mentioned that the output of the diodes are connected to a Schmitt Trigger circuit to make the output voltage in a logical level and at the same time canceling out the disturbances on the waveforms [11]-[13].

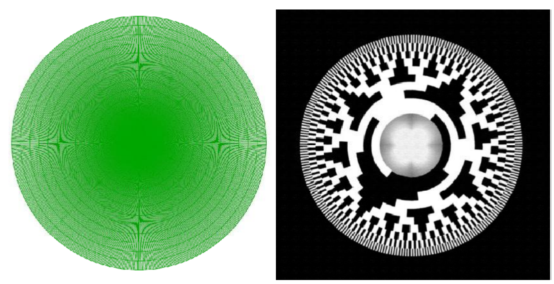


Fig. 17. Designed 10 bit encoder system

To measure and monitor the motor speed characteristic, in this paper, the encoder output pulses are transferred to the computer using microcontroller and USART serial communication algorithm. Figs. 18 and 19 show the overall practical setup and the implemented inverter.

5.3. Design Methodology

In this section, the design procedure of a PCSPIM open loop drive system is discussed. Different parts of a drive system are introduced and for each part, the design considerations are mentioned. Using the practical implementation, the performance of the designed drive system is tested to run and control the speed of a 100W PCSPIM [9].

In the following, different parts of the system are introduced:

1. Voltage source inverter (VSI): As mentioned before, SPWM pulses are used as signals to drive the inverter's switches. A VSI contains a DC-link, processing unit, switching bridge, driving system of the switches, and protection circuit [9].

1.1. DC-Link: SPIMs are widely used in household applications where single phase power supply (220-240V, 50-60Hz) is available. The single phase power supply should be rectified to create the DC-Link. The peak amplitude of the single phase power supply in Iran is about 312 V.

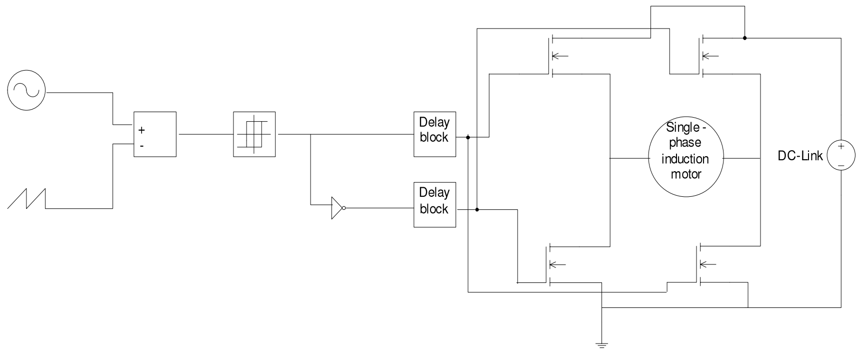


Fig. 11. SIMULINK model of a PCSPIM

4.2. Simulation of SPIM

The dynamic model of a PCSPIM is completely represented in reference [12]. Both d and q axis of the equivalent circuits are shown in Fig. 10. The final dynamic models are represented as follow [13]:

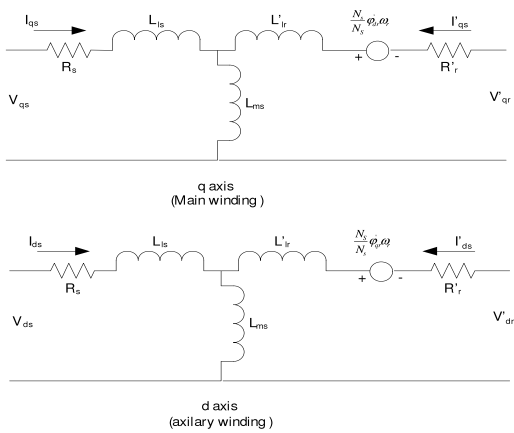
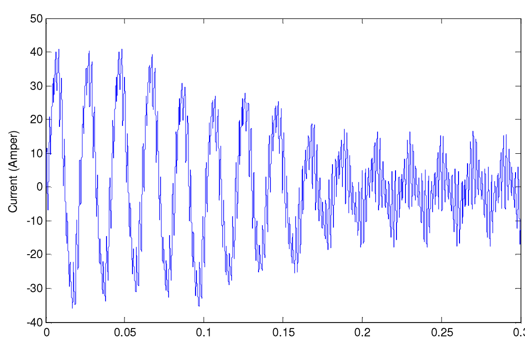


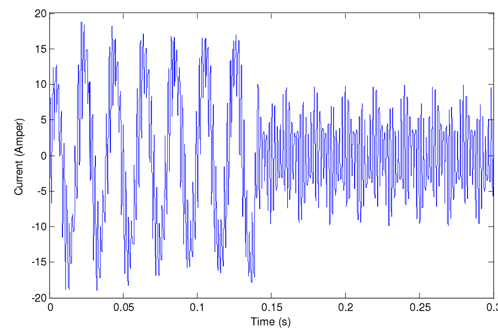
Fig. 10. SPIM dynamic model

The above mentioned model can be simulated in MATLAB/SIMULINK as shown in Fig. 11.

It is obvious that induction motors act like transformers and the self-inductance of the coils acts as low pass filters which removes the higher order harmonics of applied voltage. The current and produced torque of the main and auxiliary windings of the motor is shown in Figs. 12 and 13.

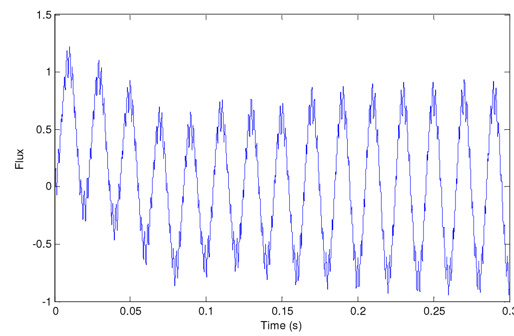


(a)

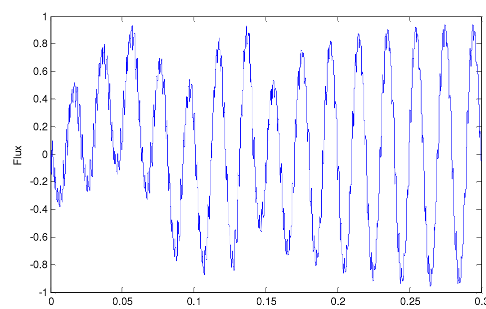


(b)

Fig. 12: Current of the (a) Main and (b) Auxiliary windings



(a)



(b)

Fig. 13. Produced torque of (a) Main and (b) Auxiliary windings

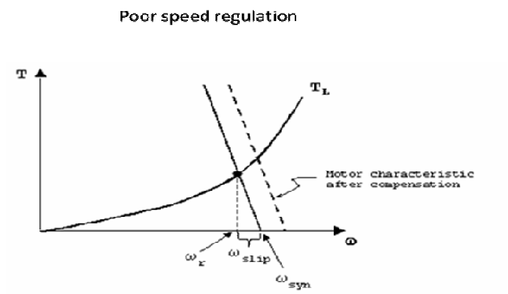


Fig. 4. Speed regulation and slip compensation

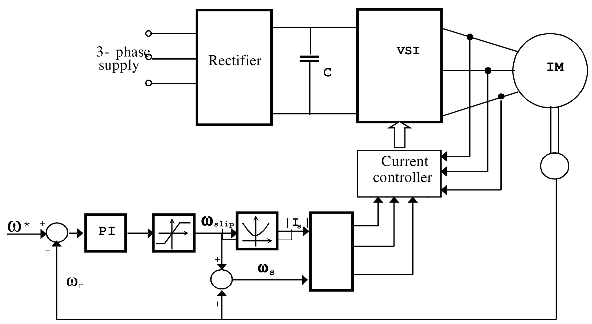


Fig 5. Close loop control block diagram

4. Design and Simulation

In this section, the main tools and information needed to implement the open loop control system is designed and simulated.

4.1. Generation of Sinusoidal PWM (SPWM)

Different methods can be used to generate switching pulses in an inverter. Among all of them, one which generates lower harmonics should be used in the system and the controlling cycle. References [9] and [10] have introduced different methods and their characteristic.

SPWM is the best approach to generate switching pulses wherein a control signal is being compared with a triangular wave to generate an SPWM wave. The basic concept of SPWM generation is shown in Fig. 6.

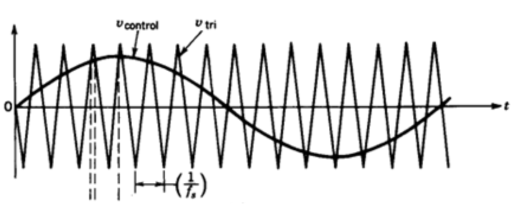


Fig. 6. Sinusoidal Pulse Width Modulation principals

In order to specify an SPWM pulse, two parameters should be defined, amplitude ratio (ma) and frequency ratio (mf) [2] and [13]. Amplitude ratio plays the most important role in output voltage amplitude and is defined by the control signal. It is important to note that the constraint of ma<1 should be considered. Otherwise the output voltage will be distorted with huge harmonic components [11]. Frequency ratio is defined by the characteristic of the power switches and desirable harmonic characteristic of output voltage. Higher frequency ratio causes low harmonic components which can be eliminated using simple high-pass filter. As authors in reference [2] and [9] have also discussed, the frequency ratio should be always odd so that the even harmonic components eliminated from output voltage. Using MATLAB/ SIMULINK, SPWM output waveform can be simulated. SPWM can be generated by using microcontrollers in practice. The block diagram of the system is shown in Fig. 7, considering that the triangular waveform frequency is 550Hz which means that mf=11 as shown in Figs. 8 and 9.

It is obvious from Fig. 9 that the third harmonic is really low in this approach and it can be removed by machine impedance without needing any specific filter. This result is very important and it helps to have better power quality by using SPWM.

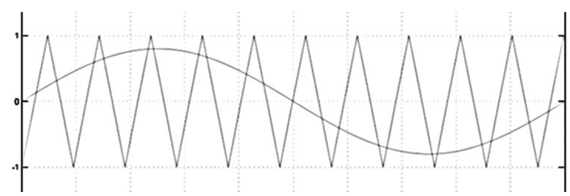


Fig. 7. Control signal and triangular wave

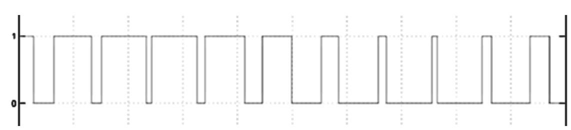


Fig. 8. SPWM waveform (mf= 11, f= 550Hz)

The harmonic components of the SPWM waveform are shown in Fig. 9.

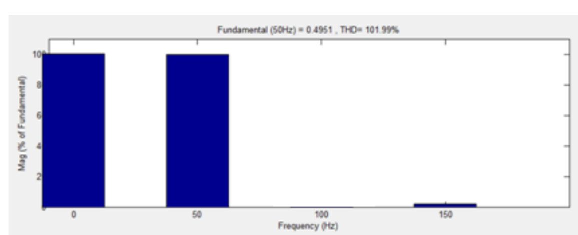


Fig. 9. Harmonic components of the simulated SWPM waveform

2. SPIM Model

SPIMs are usually low power machines which are widely used in industry and home applicants. This motor has not starting torque and needs a starter to let it rotate. Because of this fact, the SPIM operate with auxiliary windings having inductive or capacitive characteristics.

An induction motor is an electrical transformer in which the magnetic circuit is separated by an air gap between the stator winding and the moving rotor winding [1]. The equivalent circuit can accordingly be shown either with equivalent circuit components of respective windings separated by an ideal transformer or with rotor components referred to the stator side as shown in Fig. 1.

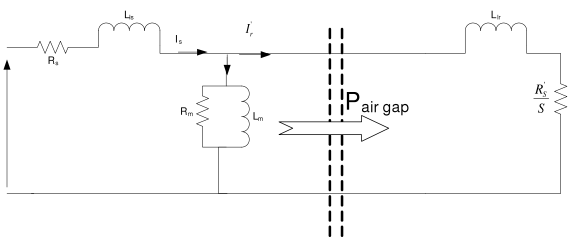


Fig. 1. SPIM equivalent circuit

Conventional notation is used for machine parameters and variables. The synchronous speed Ns and motor slip is determined by using the following equations:

$$Ns = 120\frac{f}{p} \quad (1)$$

$$Slip = 100\left(\frac{Ns - Nr}{Ns}\right) \quad (2)$$

Parameters f and p are electrical frequency and the number of machine poles respectively. Also Nr is the rotor speed.

3. Scalar Control of Induction Motor

Generally, steady state speed of an induction machine can be controlled in three scalar control approaches. First approach is changing the number of poles of an induction machine. This method changes the synchronous speed in discrete steps. Another approach is to change the amplitude of the voltage supply while the frequency is fixed. In this method, slip becomes high as voltage reduced. The last and at the same time the best way to control the speed of an induction machine is accomplished when power electronics converters are used to make variable frequency and variable power supply voltage [8]. In this method always the ratio of voltage amplitude to the frequency is kept constant and is called "constant V/f" approach.

3.1. V/f= cte speed control method

Using power electronics technology, the value of AC voltage amplitudes and frequency can be controlled. Constant V/f approach controls the supply voltage's amplitude and frequency in a way that a constant air-gap flux is achieved. Speed will be adjusted by varying frequency and at the same time V/f ratio will be kept constant.

In this way, torque-speed characteristic of the induction machine will be shifted to left or right by changing the frequency [9]-[12], but the peak of the characteristic remains constant as shown in Fig. 2.

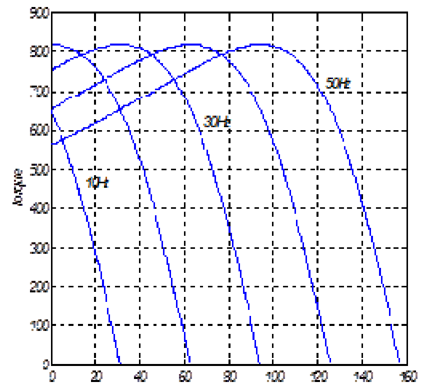


Fig. 2. Torque-speed characteristic of an induction motor by changing the frequency while V/f is kept constant

3.2. V/f constant Open-loop control

Fig. 3 is depicted the block diagram of open loop control for V/f constant approach. In this approach, system tries to achieve a specific speed using torque-speed characteristics of the machine [12]. As shown in Fig. 3, reference speed determines the voltage amplitude that is needed to be supplied to the machine. The determined voltage will be supplied to the machine using a voltage source inverter [13].

This approach is simple but suffers from several problems. Firstly, at low speeds, voltage drop across stator impedance is significant compared to air-gap voltage and causes poor torque capability at low speeds. One solution for this problem is to boost the voltage at low speed while maintaining the magnetizing current (Im) constant to achieve a constant air-gap flux.

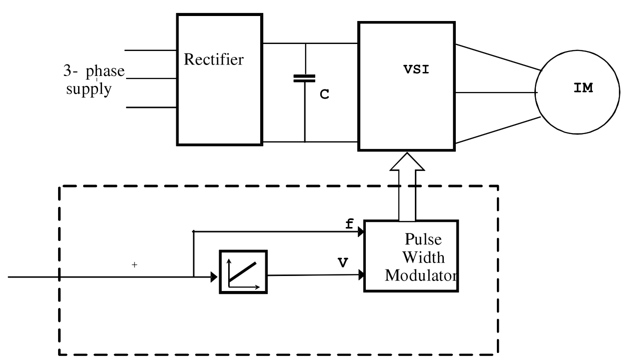


Fig. 3. Block diagram of open-loop control approach

The other problem with open loop control is the poor speed regulation in this strategy. To fix this problem slip compensation and close loop control can be used as shown in Figs. 4 and 5.

In this paper, the design and practical implementation of an open loop control method for SPIM in home appliances is discussed.

A V/f= cte Control Drive for Permanent Capacitor Single-Phase Induction Motor

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Abstract
Poor performance of the convectional household induction motors which used in home appliances such as refrigerator, cooler, laundry, washing machines, fans, hand-held power tools, and automotive window lift is generally caused by two main reasons. Firstly, they have high starting current which causes significant voltage drop, and secondly, they operate in a single speed mode and not in variable speed. In many home appliances, traditionally a discrete speed control method is used by changing the number of the poles. A proper solution for these problems can be achieved by using control drive systems. In this paper, a simple scalar control method is applied to control the speed of a permanent capacitor single phase induction motor (PCSPIM). The philosophy of this method is on the basis of simultaneous system's frequency and voltage control on the machines terminals subject to V/f=cte. Simulation and practical implementation results clearly show the effectiveness of the simple V/f =cte speed control method for home appliances.

Index Terms
Single-phase induction motor (SPIM), speed control, V/f = cte, SPWM.

1. Introduction
Attempting to achieve the best options has always been one the appealing concepts in the philosophy of control. Single phase power supplies are inevitable electrical energy sources in low power industrial and household applications. SPIMs are one of the most popular kinds of electrical motors that widely used. Home appliances are using SPIMs and this cause a poor performance for them due to the presence of huge starting currents. Also SPIMs suffer from the limitations on the rotational speed and two step discrete speed control with changing the number of their poles. The authors in [1] have discussed the changing of pole number to change the rotational speed of a single phase induction machine. The complexity of the method and non-ideal behavior of the system during changing the poles procedure is obvious. The authors in [2] have discussed the newest method to drive and control the speed of the SPIM. In most of these applications there is a move away from analog motor control to precise digital control of motors depending on the application.

In different studies, scalar speed control method is implemented for a single-phase induction machine. Some of these studies are constructed to mitigate the practical problem such as loss minimization in scalar-control of induction motor drives (IMD) with search controllers (SC) [3]. In [4] different practical problems that may be occurred during the driving of an induction motor using voltage source converters is reported. The proposed solution for this problem is open loop scalar control of induction motor. In this paper these problems and their solution has been considered in designing of the single phase voltage source inverter. It is shown in [5] and [6] that in V/f =cte control of a SPIM, the rotor speed can be controlled based on torque-slip characteristic by holding the machine torque constant; but in [6] there is no practical implementation. In [7], a space-vector pulse width-modulation (SVPWM) inverter is proposed for constant-power operation of a two-phase induction motor. Considering all the above methods, it should be mentioned that it is not necessary to have a complex drive system for many household applications. In line with this fact, the important constraints on design and implementations are: low price, low maintenance requirements, low complexity and low power dissipation.

In this paper the design procedure of a V/f=cte speed control method is discussed. Results presented in this paper were obtained from a collaborative research project with a home appliance company. The simulation results and practical implementation of the designed system shows the effectiveness of the simple V/f =cte speed control method for home appliances.