



Matlab Design of Variable Frequency Drive to Control a Submersible Water Pump based on Photovoltaic Energy

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Abstract— This paper, provides the design, modeling and simulation of a Variable Frequency Drive (VFD) with LC filter for a water irrigation pump. The design of three-phase inverter is based on PWM generator where this PWM generator is designed by another PWM generators subsystem. The testing of circuit and of voltage signals is also done with and without LC filter. The formulation and calculation of control system is based on voltage to frequency ratio (V/F) where it is expected to keep constant the speed of motor while frequency changes from 30Hz to 50Hz.

Keywords—Variable Frequency Drive, Water Pumping, PWM Generator

I. INTRODUCTION

As known, pumps are divided into two categories, diesel and electric pumps. When electric pumps are used, the more sustainable and eco-friendly way to electrify them is by solar arrays. Feeding pumps from PV requires the inverting of the variable DC voltage to a constant AC signal and this can be done through DC / DC converter then DC / AC inverter [1]. The complete block diagram of PV – Motor is as shown in Fig. 1.

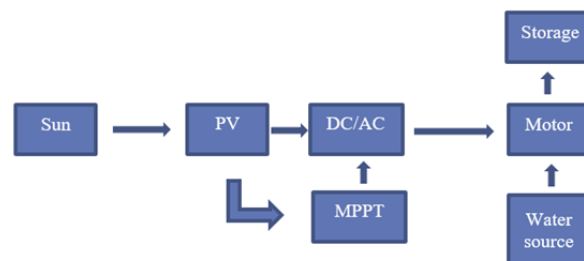


Fig. 1: Block Diagram of PV – Motor Drive

Fig. 2, shows an electric submersible pump that offer portability, easy handling and such pumps are generally available in a power rating and capacity range that makes them well suited for several PV working sites. They are used in irrigation and in other applications where diesel pumps cannot



be used, for example underground mining or where emissions are not allowed. Current manufactures' [2] medium to large capacity ranges, offer maximum power rating of 54KW and can typically manage flows from 3.75 to 275 L/s with a maximum head of 85 m. These are the typical range; however, some higher-head pumps are available on the market.



Fig. 2. Electric Submersible Pump

Moreover, electric submersible pumps used in the toughest applications should be equipped with hardened impellers to handle suspended solids [2]. There are many configurations of solar pumping as shown in Fig. 3.

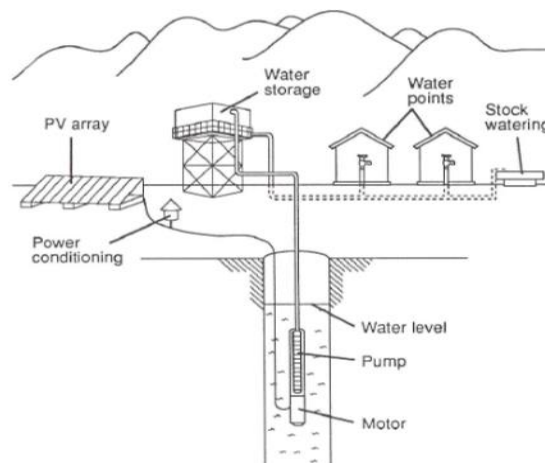


Fig. 3. Solar pump Configuration

VARIABLE FREQUENCY DRIVE

Variable Speed Drive (VSD) or Variable Frequency Drive (VFD) is used in many industrial applications to control the speed of motors such as fans or pumps. The VFD consists of four main parts as shown in Fig. 4:



- 1) AC to DC Converter (Rectifier)
- 2) DC Link
- 3) DC to AC Converter (Inverter)
- 4) Control Circuit

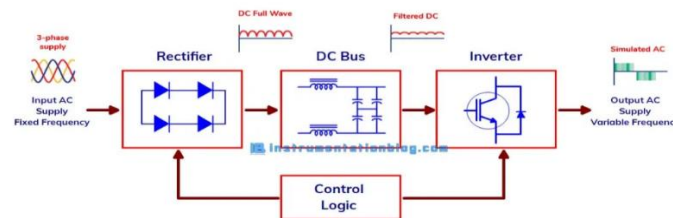


Fig. 4: Sections of VFD

The converting DC to AC voltage of VFD is called Pulse Width Modulation (PWM).

Pulse width modulation uses transistors that can be switched ON or OFF. The DC voltage is in a sequence to produce the desired AC output voltage and frequency 50Hz. IGBTs (Insulated Gate Bipolar Transistor) are used as a transistor in VFD. The below figure Fig. 5, shows the typical configuration of IGBTs in the inverter section of VFD:

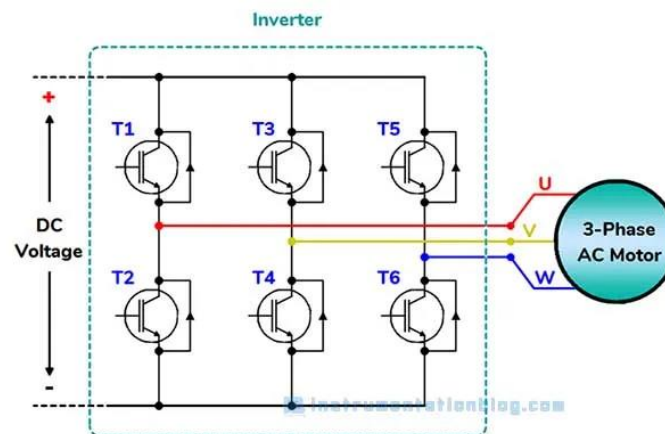


Fig. 5: Inverter Circuit Using IGBT Transistors

The one transistor on the top portion of the diagram and one at the bottom of the diagram must be activated to flow the current between two phases of the motor. Current can be induced in either direction between phases by utilizing the right combination of transistors.



II. MATLAB DESIGN OF VFD SIZING

The chosen motor pump rating is suggested as high efficiency 3.7kW [3] with the following ratings as stated in Table I.

I. MOTOR SPECIFICATIONS

Power [kW]	HP	Voltage [V]	FLC	cosΦ
3.7	5	380	8	0.82

The VFD size depends on the total watts of the load used in general, it should be about 25%-30% larger than the total watts of the pump.

$$VFD\ size = 1.3 * 3.7kW = 4.81kW$$

According to the above calculations, the chosen inverter or the variable frequency drive has the following specifications [4] as shown in **Error! Reference source not found.II**:

I. VFD SPECIFICATIONS

Rated Output Power (kW)	5
FLC	8
Output Voltage	380
Max DC Voltage (V)	400
Start-up Voltage (V)	200
Lowest Working Voltage (V)	150
Recommended DC Input Voltage Range (V)	200-400
Recommended MPP Voltage (Vmpp)	330

By using MATLAB software the system was designed and built to see the results. First of all, a three-phase inverter was designed to convert the output DC voltage to alternating current on the AC induction motor terminals. So, a PWM generator was designed firstly as shown in Fig. 6.

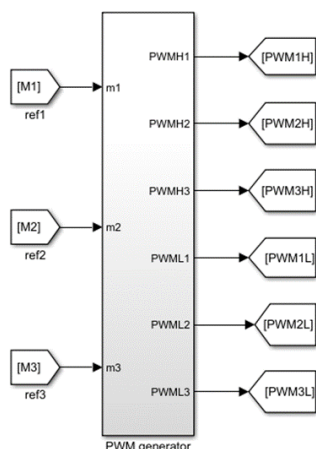


Fig. 6: PWM Generator by MATLAB

The PWM generator has 6 pulsating outputs that will be connected to the SCRs on the inverter side. Each signal pulse block has a carrier frequency of 7500 and have 2 output. However, the input for these blocks are the three outputs from the frequency voltage feedback controller, which will be shown below. Secondly, the inverter was designed as shown in Fig. Each SCR has a different PWM signal from the PWM generator to convert DC to AC.

Meanwhile, Fig.7, **Error! Reference source not found.** shows how the PWM generator is designed from subsystem.

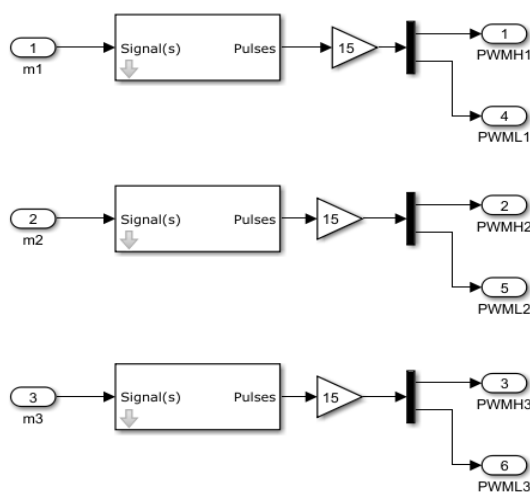


Fig. 7: PWM Generator Subsystem.



VDC1 is the voltage reference in the circuit rated at 349V as the output of the PV panel string as seen in Fig. 8.

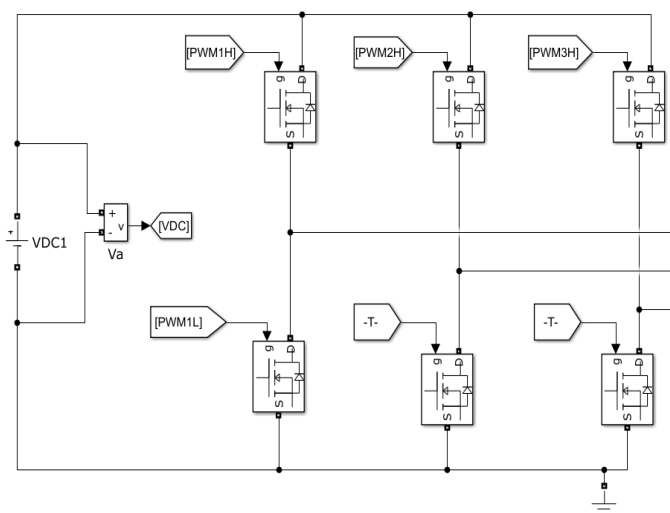


Fig. 8: Three Phase Inverter Design

Moreover, a LC filter was added after the inverter connections to generate a pure sine wave signal for the motor as shown in Fig. 9.

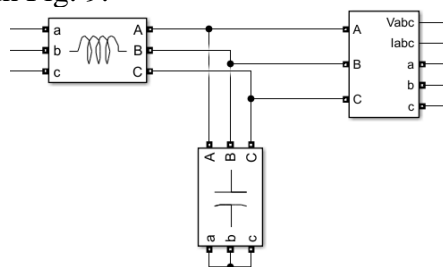


Fig. 9: LC Filter

Finally, the design has an open loop modulation index and frequency feedback controller. As shown in Fig. 10, the design starts with 5 inputs: the rated voltage V_{rms} , rated frequency, number of poles pairs, rated speed and VDC1 reference DC voltage. Through this unit and after connecting the motor, any change in frequency, voltage, and rated RPM the system will support rapidly the motor to stay functioning on a stable speed.

In this unit controller there are 5 inputs:

1. Rated Voltage.
2. Rated frequency.



3. Number of Poles Pairs.
4. DC input voltage.
5. Rated Speed

Then we have 2 functions

1. Inverter frequency.
2. Modulation Index

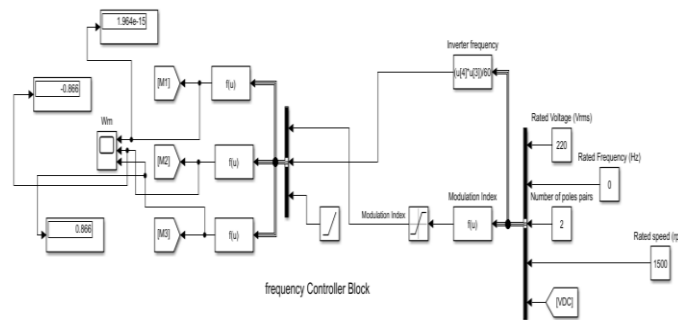


Fig. 10: Frequency Controller Design

a) *Inverter Frequency:*

The equation of the inverter frequency depends on the rated RPM and number of poles pairs.

$$Frequency = \frac{Num. Poles \times RPM}{60} \quad (1)$$

This will calculate the frequency required by the user to control the motor speed.

b) *Modulation Index:*

The modulation index is a function that calculates the rated voltage over the DC voltage obtained from the system with the following equation below:

$$Modulation Index = \frac{2\sqrt{2} \times Rated Voltage}{\sqrt{3} \times VDC} \quad (2)$$

Finally, we will obtain 3 functions:

- $Rated\ voltage \times \sin(F \times 2 \times \pi \times Pole\ Pairs)$ (3)
- $Rated\ Voltage \times \sin\left(F \times 2 \times \pi \times Pole\ Pairs - 2 \times \frac{\pi}{3}\right)$



(4)

➤ $Rated\ Voltage \times \sin(F \times 2 \times \pi \times Pole\ Pairs + 2 \times \pi/3)$

(5)

Based on these 3 functions that depend on the input of the controlling unit, the PWM generator will operate and maintain a constant speed when varying loads and a user control over the speed of the motor.

II. SIMULATION AND RESULTS

The *Voltage / Frequency* controller is the unit where the rated frequency and rated voltage V_{rms} , are set. In this study, the rated voltage is 380V and the rated frequency is equal to 50 Hz. Moreover, there are 2 more inputs on the controller unit, the number of pole pairs equal to 2 and the DC voltage from the PV panels is given as 349.69 V as shown below Fig 11.

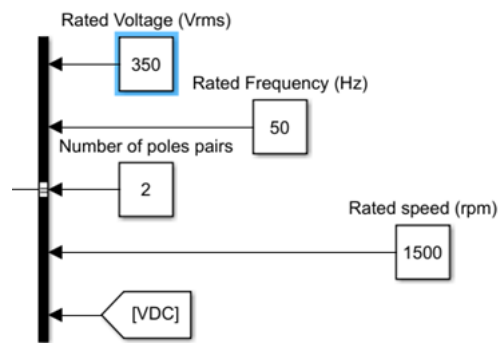


Fig. 11: Controller Unit Inputs

The controller unit will do some calculations as follows:

1) managing the frequency of the inverter by changing the rated speed, by increasing it or decreasing it.

$$Frequency = \frac{2 \times 1500}{60} = 50$$

2) the modulation index formula as follows:

$$Modulation\ Index = \frac{2\sqrt{2} \times 380}{\sqrt{3} \times 350} = 1.7$$

Which then is set to a saturation block to 1.



3) The output of this unit can be reached by 3 voltage functions with a 120° shift as shown in Fig. 12.

$$F1 = 380 \times \sin(200\pi)$$

$$F2 = 380 \sin(200\pi - 120)$$

$$F3 = 380 \times \sin(200\pi + 120)$$

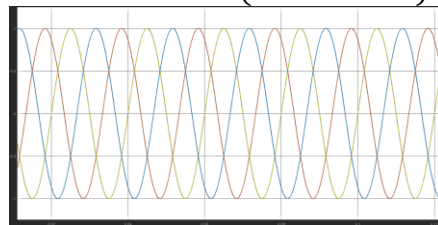


Fig. 12: Controlling Unit Output

So, the V/F controller is producing 3 sinusoidal functions based on the frequency controller block and the 3 functions mentioned in the previous section. The amplitude of these functions is limited to 1. Moreover, these functions will enter the signal generator of the PWM generator to monitor the gates of the Inverter. In the following sections, signals will be discussed at different stages of Inverter.

A) AT PWM GENERATOR

The PWM generator adds up 2 signals one from the frequency voltage control and one from the signal generator which has a carrier frequency of 7500Hz. As shown in Fig. 13. the upper graph is the input signal and the lower graph shows the summation of the input and signal generator graphs.

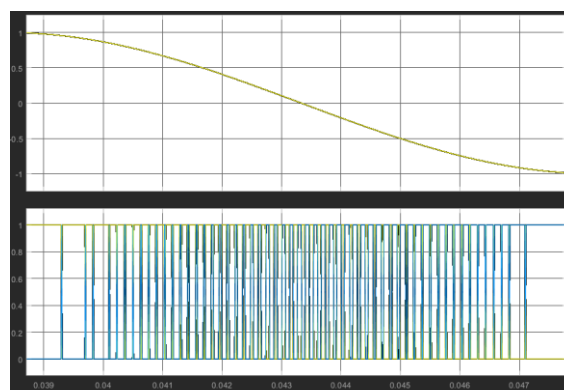


Fig. 13: Input Signal Vs. Output Signal of PWM Generator



The graph in Fig shows the low and high pulses from the PWM generator. The output of the PWM generator will be 6 signals 3 high and 3 low.

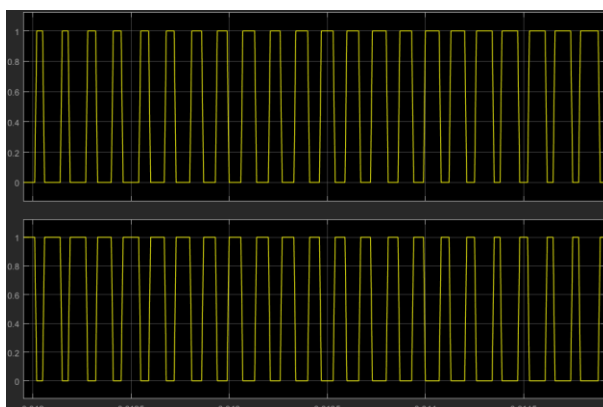


Fig. 14: High and Low PWM Pulses

B) INVERTER OUTPUT

The output of the inverter before adding LC filter is shown in Fig 15. The inverter without the filter will produce a square wave signal.

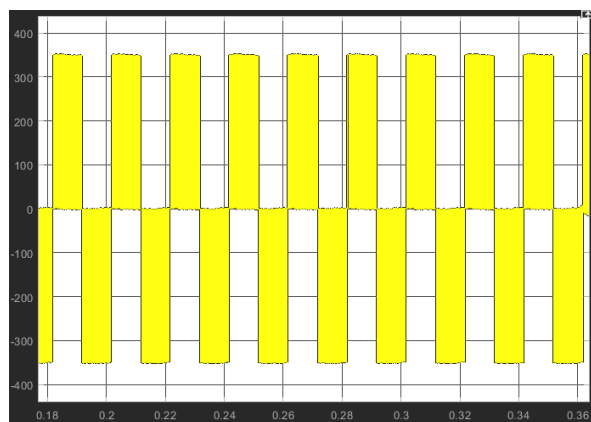


Fig. 15: Inverter First Output

After adding an LC filter to the inverter, now it can produce a pure sinusoidal wave for the pump as shown in the Fig. 16. The LC filter is made up of some series inductors on the 3 phase lines and capacitors in parallel on the 3 phase lines.

The value of the inductance and capacitance of the filter as follows $L = 5.39 \text{ mH}$, $C = 2.93 \mu\text{F}$

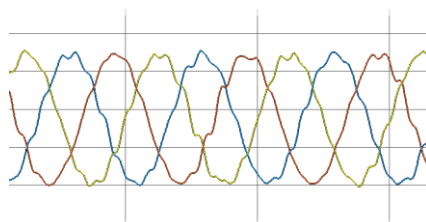


Fig. 16: Input Voltage Wave

On the other hand, Fig. 17, shows the current of the motor when the Motor is loaded.

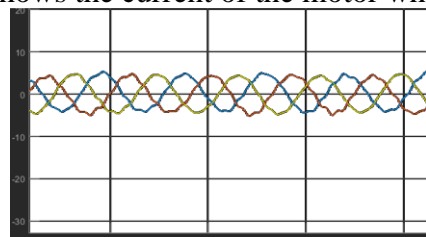


Fig. 17: Current Wave of the Motor

C) TESTING THE MOTOR

Now a small test will be done to see the function of the motor if the rated frequency drops down. First the simulation took place when the motor ran on normal conditions then it was tested on two different frequencies 30Hz and 20Hz as shown in **Error! Reference source not found..**

III. MOTOR SPEED AT VARYING RATED FREQUENCIES

F=50		F=30		F=20	
Load	Speed	Load	Speed	Load	Speed
0	1500	0	1499	0	1499
1	1499	1	1490	1	1487
2	1499	2	1485	2	1483
3	1499	3	1479	3	1479
4	1498	4	1473	4	1471
5	1498	5	1469	5	1468

It is very clear that efficiency of the inverter reach 97% even for low frequency input due to low irradiation at PV panels. The system will enable to pump up 90% (as minimum) more water if the average sunning hours that is not enough to provide 50Hz is more than 100% daily while in [5], it pump up 87% more water than system without maximum power point tracking MPPT.



CONCLUSION

The Table III shows clearly that the variation of rated frequency from 20 to 50Hz it will not affect the rated speed of motor where the variation does not exceed 2.5% for the worst case of input frequency 20Hz or 30Hz at the full load of the motor. As a conclusion, the frequency driver is working well on managing the input frequency of the motor and keeping it functioning on a constant speed even for a low input frequency and high torque load and this improve the energy efficiency of the motor to the maximum values and pump up more water even for low irradiation of the sun (at morning or afternoon).

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