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International
Journal
Of Modern Engineering Research (IJMER)

Compensation for Inverter Nonlinearity Using Trapezoidal Voltage

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Abstract: *The nonlinearity of an inverter can be considered as the voltage differences between the voltage references and actual outputs of the voltage source inverter (VSI). In this paper, trapezoidal voltages were utilized to compensate for the inverter nonlinearity. The harmonic distortions in the output currents caused by the inverter nonlinearity can be controlled through the trapezoidal angle. Simulation results are given to demonstrate the validity and features of this method.*
Keywords: *Inverter nonlinearity, dead time compensation, trapezoidal voltage, harmonic analysis, Induction machine.*

I. Introduction

Inverter fed ac drives are normally used in industrial application which reduces the cost for motors and its maintenance and providing maximum power savings. Behavior of the inverter influences the performance of ac machines. The nonlinear characteristics of switching devices such as dead time, switch turn on/off time delay, and voltage drop across the switches and diodes in inverters produce voltage distortion. The most significant nonlinearity is represented by the dead time to avoid short circuit of inverter legs. Voltage drop and turn on/off time inevitably exist in practical devices. However, dead time causes voltage error in the voltage source pulse width modulation (PWM) inverter by producing unwanted harmonics. In case of sensor less drives, this distortion usually causes a non optimal motor exploitation at low speed operation due to an error in the estimated position of the adopted reference frame used by the motor control scheme. In addition, the motor currents will be distorted, resulting in unnecessary torque ripple.

Various solutions have already been suggested to avoid the nonlinear characteristics of the inverter. [1], [2]. In most cases, compensation techniques are based on an average value theory and the lost volt seconds are added vectorially to the voltage reference. In a pulse-based compensation method the compensation is realized for each pulse width modulation (PWM) pulse. Meanwhile, other attempts have been carried out using the disturbance observer [3]. In these methods, the inverter nonlinearity is regarded as the disturbances to be mitigated. To estimate the disturbance voltages, the observer, used which is expected to be effective for a wide operating range. However, electrical parameters may vary depending on the circumstances, are used to design the observer. That is, the performance of the observer would be limited by the operating conditions.

In this paper, a novel method was proposed to compensate for the low-order harmonics from the inverter nonlinearity. The proposed method is similar to the observer-based method, in that the nonlinearity is regarded as voltage distortions. However, the proposed compensation method can adapt to varying operating conditions without the aid of any observers.

II. Analysis Of Dead Time Effects

Due to definite turn-off and turn-on times of the switching devices in PWM inverters, it is necessary to insert a time delay between the switching OFF of a device and the switching ON of the other device on the same inverter leg. Fig 1 shows one phase of a PWM inverter.

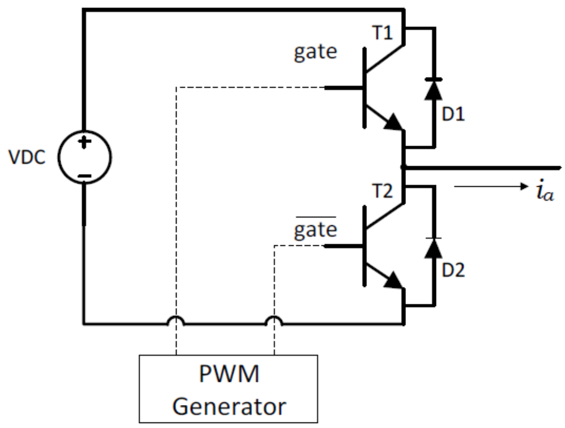

Fig 1.Single phase configuration of PWM inverter

Fig 2 shows the time delay (t_{dead}) between the switches T1 and T2. TON is the time for which the switch T1 is ON. T_{SW} is the switching period. At time t1, T2 transitions from ON to OFF. The turning ON of T1 is delayed by time t_{dead}. This prevents the short circuit across both the switches of the inverter leg and the input dc voltage source. The introduction of the time delay between switching leads to reduced and distorted voltage at the output of the inverter.

To examine the effect of dead-time on the output voltage, switching waveforms on one leg of the inverter are examined. The current i_a is positive in the direction of the load. The IGBTs T1 and T2 conduct when they are ON. During the dead-time period, when both T1 and T2 are OFF,

Either the reverse recovery diode D1 or D2 will conduct depending on the direction of ia.

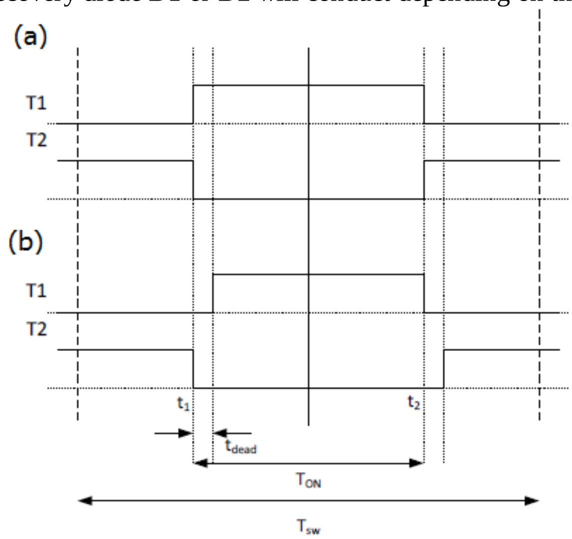

Fig 2. Time delay between turn OFF and turn ON of two switches on the same inverter leg (a)Ideal switching (b) Switching with dead time

Depending up on the direction of the switching transition and the sign of the current in phase 'a' i_a, four conditions are possible.

- The current i_a is positive, T1 transitions from ON to OFF, T2 transitions from OFF to ON: During the dead-time period, D2 conducts and D1 blocks the flow of current. Thus, this condition results in the correct voltage being applied to the load terminals.
- The current i_a is negative, T1 transitions from ON to OFF, T2 transitions from OFF to ON: During the dead-time period, D1 continues to conduct and D2 blocks the flow of current. And the condition results a gain in the voltage which being applied to the load terminals.

• The current i_a is positive, T1 transitions from OFF to ON, T2 transitions from ON to OFF: During the dead-time period, D2 continues to conduct and D1 blocks the flow of current. And the condition results in a loss of voltage being applied to the load terminals.
• The current i_a is negative, T1 transitions from OFF to ON, T2 transitions from ON to OFF: During the dead-time period, D1 continues to conduct and D2 blocks the flow of current. And the condition results in the correct voltage being applied to the load terminals.

In each switching cycle, T1 transitions from OFF to ON (T2 from ON to OFF) once and from ON to OFF (T2 from OFF to ON) once. Due to the distortions, the output voltage of the inverter is not equal to the desired reference voltage. In order to overcome the effect of dead time the proposed method has been suggested.

III. PROPOSED METHOD

In proposed method, voltages in a trapezoidal form were utilized to compensate for the inverter nonlinearity. This method can adapt to varying operating conditions and physical parameters are not necessary for the adaption. [4]. An averaged model of the inverter was taken and averaged for one sampling period, to consider the temporal distortions. Then the inverter nonlinearity is entirely separated as the nonlinear loads whih is D (i_{as}), D (i_{bs}), and D (i_{cs}).

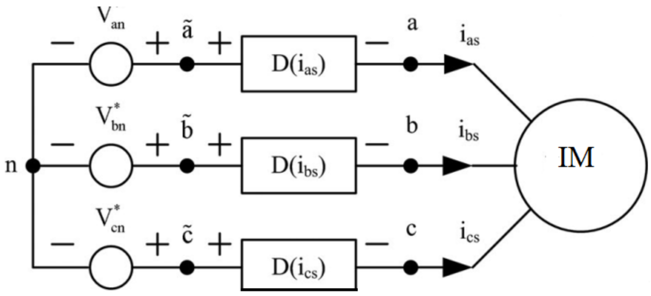

Fig 3. Modeling of an inverter: averaged inverter model per one sampling period

The compensation principle is clarified with Fig 3

$$V_{xx} = -D\,(i_{xs}) + V_{inv}^{x} = 0 \qquad (1)$$

Where the phase "x" can be a, b, or c and D (i_{xs}) is the distorted voltages and V_{inv}^{x} is the compensation voltage which is added to the reference. To find the magnitude of compensation voltage, IM runs at stationary condition and plot the d-axis voltage with respect to d-axis current. Select the voltage which is more saturated as (V_{A}). This V_A would be useful for compensation of the inverter non-linearity.

The compensation voltage height was determined from V_A. The trapezoidal angle Θt can be adjusted for the suitable compensation. To modulate the trapezoidal angle a dedicated modulator used. The selection of trapezoidal angle can be based on frequency analysis.

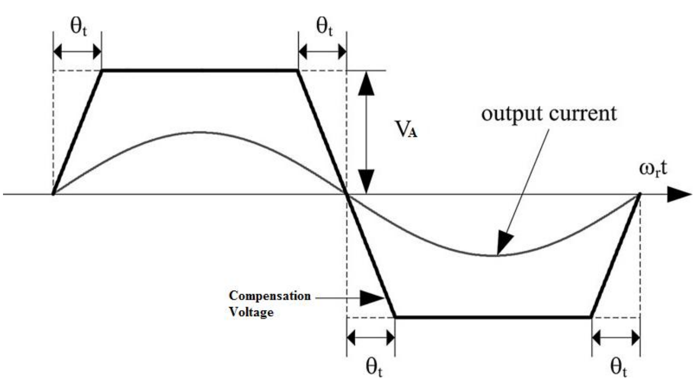

Fig 4. Shape of the compensation voltage (trapezoidal voltage).

Fig 4 showing the shape of compensation voltage and V_{sat} , Θt represent the magnitude and angle of trapezoidal voltage.

IV. MATLAB/SIMULINK ANALYSIS OF PROPOSED METHOD

A. Simulink Model Of Trapezoidal Voltage Compensation

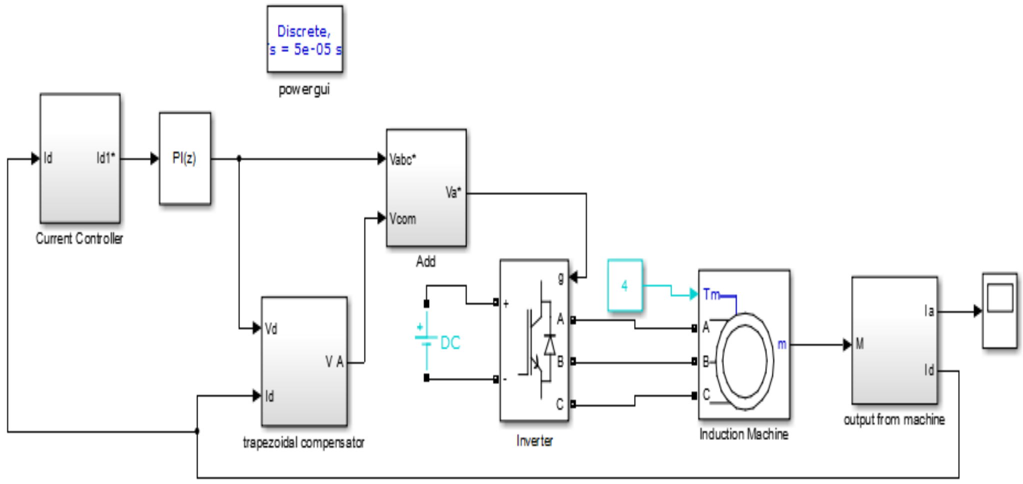

Fig 5.Simulink model for trapezoidal voltage compensation

Fig 5 shows a three-phase motor rated 10HP, 460 V; 1500 rpm is fed by a PWM inverter. The PWM inverter is built entirely with standard Simulink blocks. Its output goes through Controlled Voltage Source blocks before being applied to the IM block's stator windings. The load torque applied to the machine's shaft is originally set to its nominal value (4 Nm). The current control loop regulates the motor's stator currents. A compensation voltage generated from trapezoidal compensator block is added with the output from controller. Switching pulses for the inverter is generated by using PWM block. Hysteresis controller is used for current control. In addition, the preset dead time was 5 μs.

B.Result Analysis

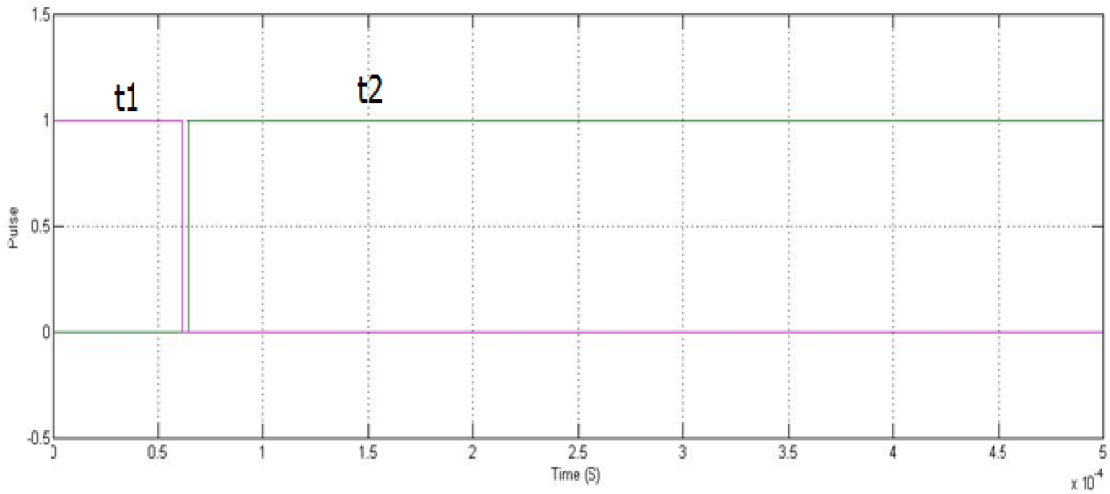

Fig 6 .Switching signal for the same leg switches with dead time

Figure showing switching pulses for switch T1 and T2 of the first inverter leg. A dead time of 5 micro second is there before T2 ON. For the compensation of inverter nonlinearity trapezoidal voltage obtained from compensation block is added to the reference having magnitude of 11V and 16.9 ^{0} angle. The angle can be varied so that at different operating condition the method is adaptable. The stator current output of IM after the compensation is shown in fig 7.

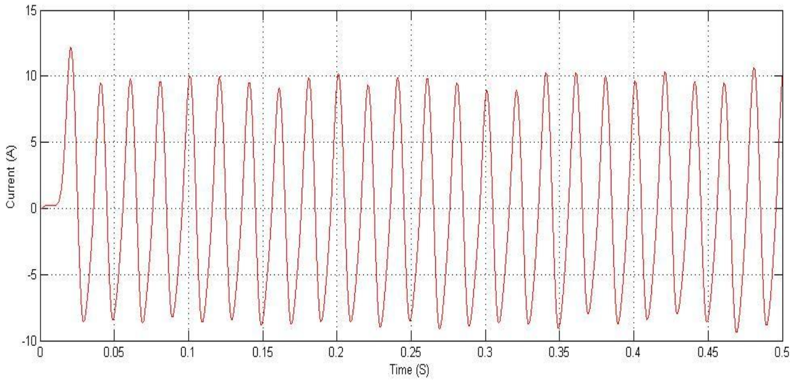

Fig 7. Stator current output (I_a) of IM

The result shows that with trapezoidal voltage compensation, the waveform distortions are getting reduced. While doing the harmonic analysis, the ratio to the fundamental (%) is varying between 20.19-16.97 .Result showing that at 16.9^0 , harmonic value is minimum and at 9^0 harmonics is maximum.

Table 1. Comparison of FFT results for the output current without and with compensation.

Ratio to the fundamental [%]		
Order of harmonics	Without compensation	With trapezoidal voltage compensation
5th	1.88	0.14
7th	2.23	0.08
11th	0.75	0
13th	0.42	0.01

The 5^{th} ,7^{th},11^{th},13^{th} order harmonics are reduced by 1.74% ,2.15%,0.75%,0.41% respectively.

V. CONCLUSION

To avoid shoot-through in voltage source inverters (VSI), a dead-time is introduced. However, such a blanking time can cause problems such as output waveform distortion and fundamental voltage loss in VSIs. To overcome dead-time effect trapezoidal voltage can be used which reduce harmonics by large amount. And it can adapt to varying operating conditions. Simulink analyze has done to validate the proposed method. Results shows that lower order harmonics and waveform distortions are decreased with proposed method .The unnecessary torque ripple with ac machine is also reduced.

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