# GENERALIZED SCALAR PWM ALGORITHMS FOR DIRECT TORQUE CONTROL OF AC DRIVES IN LINEAR MODULATION INDEX

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**Abstract:** In Direct Torque Control, the generation of inverter switching state is made to restrict the stator flux and electromagnetic torque errors within the respective flux and torque hysteresis bands so as to obtain the fastest torque response and highest efficiency at every instant. To reduce the steady state ripples and to achieve the constant switching frequency operation for the inverter, space vector pulse width modulation (SVPWM) algorithm is used for DTC based induction motor drives. However, in the classical SVPWM algorithm, the complexity involved is more. Also, it gives more harmonic distortion at higher modulation indices and gives more switching losses of the inverter. to reduce the complexity, a simplified generalized PWM (GPWM) algorithm has been proposed by varying modulation index in the linear range of control are derived at all modulation indices and the proposed GPWM algorithm will be validated through the obtained results.

***Keywords:*** **SVPWM algorithms, Direct Torque Control, AC Drives, discontinuous PWM, GPWM algorithms and simulink.**

## I. INTRODUCTION

Nowadays, in electrical vehicle drives AC motors are most commonly used. It is because of their known advantages like more reliability, simplicity, absence of mechanical commutator and brushes, ability to work under unfriendly conditions (dust, humidity, etc.) and also low cost [1]. Rated power of these drives varies from hundreds watts up to mega watts (high power applications). The most popular AC machines are induction motors and permanent magnet synchronous motors PMSM [2]. These machines be able to be supplied from power electronics converters (like VSI inverters) and hence are used in various applications like electric vehicles EV, public transport, tools drives, etc. These techniques have been invented respectively in the 1970's and in the 1980's. Though the operating principles of FOC and DTC are different, both techniques give most effective control of flux and torque of any drive [3]. These two control strategies have been implemented in many industrial applications successfully. The detailed comparison between FOC and DTC is given in [4]. However, in comparison, DTC is most popular for various applications due to its simplicity and less complexity. Due to the absence of reference phase frame transformations, DTC is simple when compared with the FOC. Though DTC gives superior torque performance, it gives variable switching frequency of the inverter and large steady state ripple in torque, current and flux. To improve the torque and current ripple, several pulsewidth modulation (PWM) algorithms have been developed by several researchers. A detailed survey of these PWM algorithms is given in [5]. These PWM algorithms can be classified into two categories such as triangular comparison approach and space vector approach. However, the space vector approach is more popular as it offers more advantages when compared with the triangular comparison approach [6]-[7]. Hence, the space vector PWM (SVPWM) algorithm is attracting many researchers nowadays. Though the SVPWM algorithm based DTC gives reduced harmonic distortion when compared with the conventional DTC, it gives dominating harmonics around the switching frequency. Hence, the acoustical noise of the motor is more. To reduce the acoustical noise of the drive, recently, generalized Scalar PWM (GPWM) algorithms are becoming popular. Various type of GPWM algorithms have been discussed in [8]-[12]. The basic principle of the GPWM algorithms is to vary the PWM pulses between 1 to 0 as per the drive requirement for reduced THD. By utilizing the freedom in zero state time distribution various PWM algorithms can be generated as explained in [13]-[15]. Many applications require an efficient PWM algorithm, which gives less total harmonic distortion (THD) in order to reduce acoustical noise and incorrect speed estimations. Hence, in recent years many researchers have been concentrated on the harmonic analysis of PWM algorithms. This paper presents carrier based generalized scalar PWM (GPWM) algorithm for direct torque control of AC drives. In the proposed GPWM algorithm by changing a constant value between 0 and 1, various PWM algorithms have been generated. Moreover, the proposed algorithm uses instantaneous phase voltages only. Thus, the proposed GPWM algorithm will bring all modulators under a common roof with reduced complexity.

## II. Classical SVPWM Algorithm

The three-phase, two-level voltage source inverter (VSI) has a simple structure and generates a low-frequency output voltage with controllable amplitude and frequency by programming high-frequency gating pulses. For a three - phase, two-level Voltage Source Inverter, there are eight possible voltage vectors, which can be represented in the space as shown in Fig. 1.

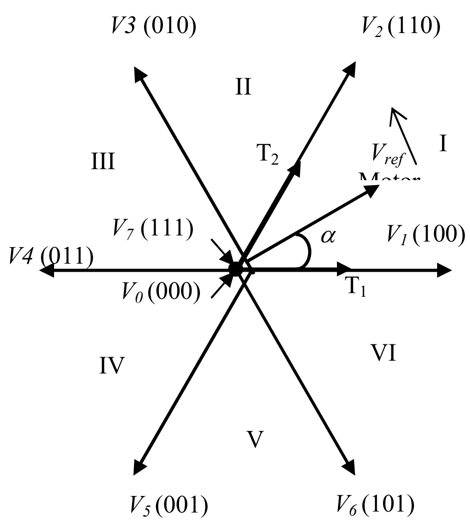


Fig. 1 Possible voltage space vectors and sector definition

The $V_1$ to $V_6$ vectors are known as active voltage vectors and the remaining two vectors are known as zero voltage vectors. The reference voltage space vector ($V_{ref}$) represents the desired value of the fundamental components for the output phase voltages. In the space vector approach $V_{ref}$ can be constructed in an average manner. The reference voltage vector ($V_{ref}$) is sampled at equal intervals of time, $T_s$ referred to as sampling time period. The possible voltage vectors that can be produced by the inverter are applied for different time durations within a sampling time period such that the average vector produced over the $T_s$ is equal to $V_{ref}$, both in magnitude and angle. It has been established that the vectors to be used to generate any sample are the zero voltage vectors and the two active voltage vectors forming the boundary of the sector in which the sample lies. For the required reference voltage vector, the active and zero voltage vectors times can be calculated as in (1) - (3).

$$T_1 = \frac{2\sqrt{3}}{\pi} M_i \sin(60^o - \alpha) T_s \quad (1)$$

$$T_2 = \frac{2\sqrt{3}}{\pi} M_i \sin(\alpha) T_s \quad (2)$$

$$T_z = T_s - T_1 - T_2 \quad (3)$$

where $M_i$ is the modulation index and defined as $M_i = \pi V_{ref} / 2V_{dc}$.

In the SVPWM control strategy, the total zero voltage vector time is equally distributed between zero vectors $V_0$ and $V_7$. Further, in this method, the zero voltage vector time is distributed symmetrically at the start and end of the sub-cycle in a symmetrical manner. Further, to minimize the switching frequency of the inverter, it is desirable that switching should take place in one phase of the inverter only for a transition from one state to another. Thus, SVPWM uses 0127-7210 in sector-I as shown in Fig 2, 0327-7230 in sector-II and so on.

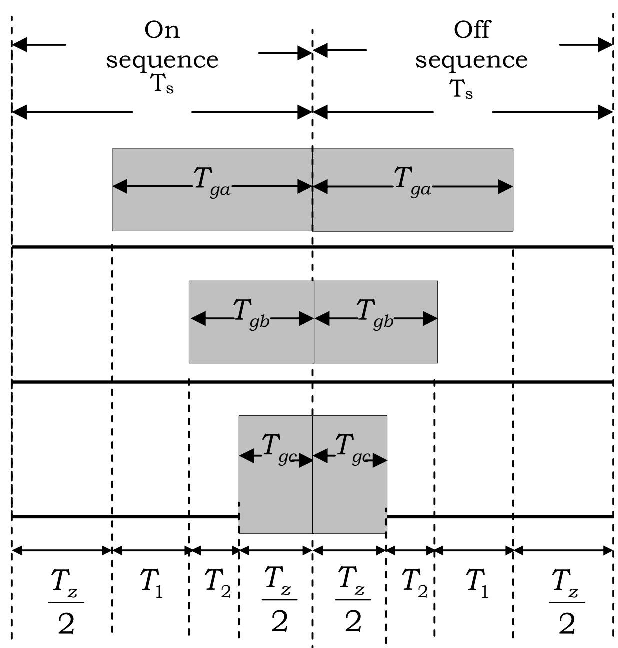

Fig. 2 Gating signal generation using SVPWM scheme in sector-I

As the classical SVPWM algorithm gives the switching times in a deterministic manner, it is also known as deterministic SVPWM algorithm.

## III. SIMPLIFIED SVPWM ALGORITHM:

As the classical SVPWM algorithm uses angle and sector information for the calculation of switching times, the complexity involved in the algorithm is more. To reduce the complexity involved in the classical SVPWM algorithm, a simplified SVPWM algorithm, which uses the concept of imaginary switching times is used. The imaginary switching time periods, which are proportional to the instantaneous values of the reference phase voltages, are defined as given in (4) [15]-[16].

$$T_{an} = \frac{T_s}{V_{dc}} V_{an} \; ; T_{bn} = \frac{T_s}{V_{dc}} V_{bn} \; ; T_{cn} = \frac{T_s}{V_{dc}} V_{cn} \qquad (4)$$

Then, in each sampling time period, the maximum, minimum and middle values of imaginary switching times are evaluated by using (5)-(7).

$$T_{\max} = Max(T_{an}, T_{bn}, T_{cn}) \qquad (5)$$

$$T_{\min} = Min(T_{an}, T_{bn}, T_{cn}) \qquad (6)$$

$$T_{mid} = Mid(T_{an}, T_{bn}, T_{cn}) \qquad (7)$$

Then the active voltage vector switching times $T_1$ and $T_2$ may be expressed as,

$$T_1 = T_{\max} - T_{mid} \; ; T_2 = T_{mid} - T_{\min} \qquad (8)$$

The zero voltage vectors switching time is calculated as

$$T_z = T_s - T_1 - T_2 \qquad (9)$$

By using equations (8) and (9), the active vector times and zero vector times can be calculated. Thus, the active state times and zero states times can be calculate without determining the angle and sector information with the help of imaginary switching times.

## IV. PROPOSED GENERALIZED SCALAR PWM ALGORITHM:

The proposed GPWM algorithm may be pursued by the definition of a duty cycle or modulating signal for phase *n* (with *n* = a, b and c), which is given as the ratio between pulse width and modulation period.

$$V_n^* = \frac{Pulsewidth}{Modualtionperiod}$$

Once the modulating signal $V_n^*$ is calculated, the ON and OFF times of the inverter-leg devices can be via digital counters and comparators. For example, the duty cycle or modulating signal of SPWM algorithm can be obtained as follows:

$$V_n^* = \frac{1}{2} + \frac{V_n}{V_{dc}}, \quad n = a, \text{b and c}$$

where $V_n$ is the instantaneous reference voltage of phase *n* and $V_{dc}$ is the dc-link voltage. In the similar way, the modulating signals of the various DPWM algorithms and SVPWM algorithms can be obtained by adding a suitable zero sequence voltage ($V_z$) to the instantaneous phase voltages ($V_n$).

$$V_n^* = k_1 + \frac{V_n + V_z}{V_{dc}} \qquad (10)$$

Where,

$$V_z = k_2[\min(V_n) - \max(V_n)] - \min(V_n)$$

where $k_2$ is the parameter that takes into account the unequal null-state sharing, can be defined as follows:

$$k_2 = 0.5(1 + \text{sgn}(\cos(3\omega t + \delta)) \qquad (11)$$

where sgn(X) is 1, 0 and –1 when X is positive, zero, and negative, respectively. As previously discussed, and $k_1$ is an additional parameter whose value may be equal to the value of $k_2$ or be fixed at 0.5. Thus, the proposed approach eliminates the calculation of both the hexagon sector, in which the reference-voltage space vector is located, and the related phase. In all the other carrier-based techniques, it must be taken that $k_1 = k_2$. The standard SVPWM algorithm can be obtained by fixing the $k_2$ value at 0.5. Similarly, by fixing the $k_2$ value at 0 and 1, the DPWMMIN and DPWMMAX algorithms can be obtained. By varying the modulation angle $\delta$, various DPWM algorithms can be generated. The DPWM0, DPWM1, DPWM2 and DPWM3 can be obtained for δ = π/6, 0, - π/6 and - π/3 respectively. .

## V. RESULTS:

To validate the proposed GPWM algorithm, several numerical simulation studies have been carried out in this paper using Matlab-Simulink. The switching frequency is taken as 3 kHz and dc link voltage is taken as 600 V. The simulation studies are carried out for modulation index of 0.6 which is linear modulation range. The simulation results of modulating wave, pole voltage, phase voltage and line voltages along with the corresponding modulating waveform for various GPWM algorithms are shown in from Fig. 3 to Fig.9.

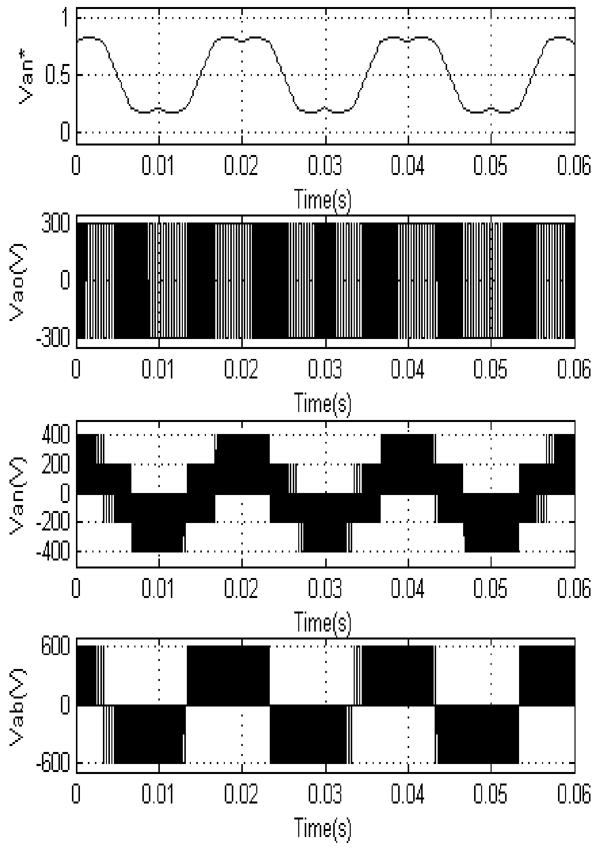


Fig. 3.Simulation results of SVPWM algorithm at modulation index of 0.6

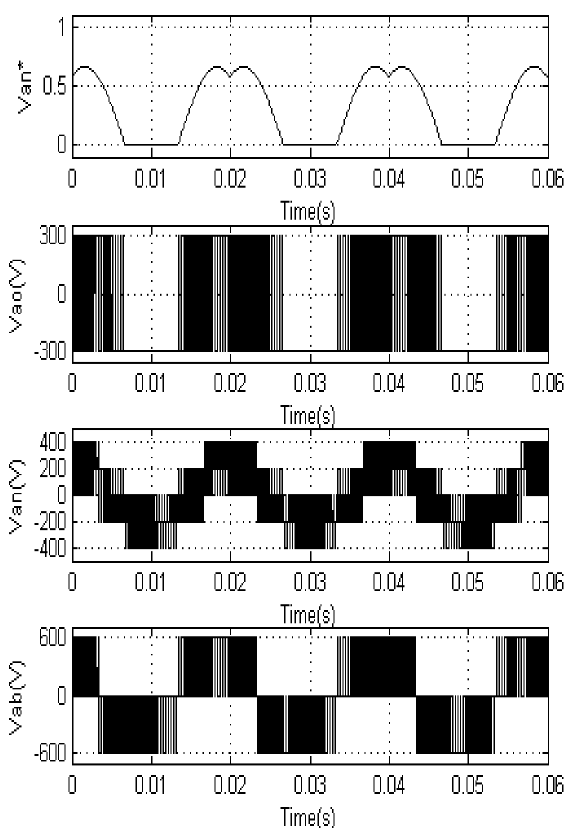


Fig. 4 Simulation results of DPWMMIN algorithm at modulation index of 0.6

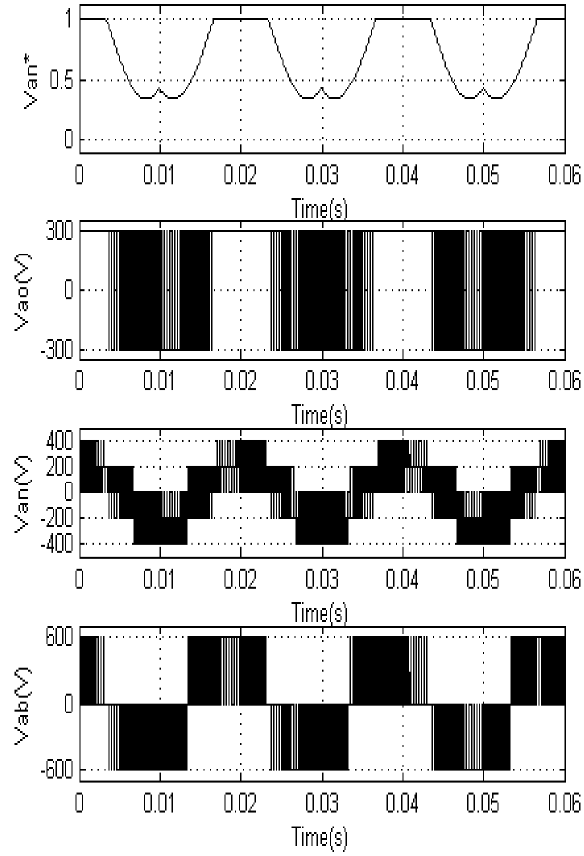


Fig. 5 Simulation results of DPWMMAX algorithm at modulation index of 0.6

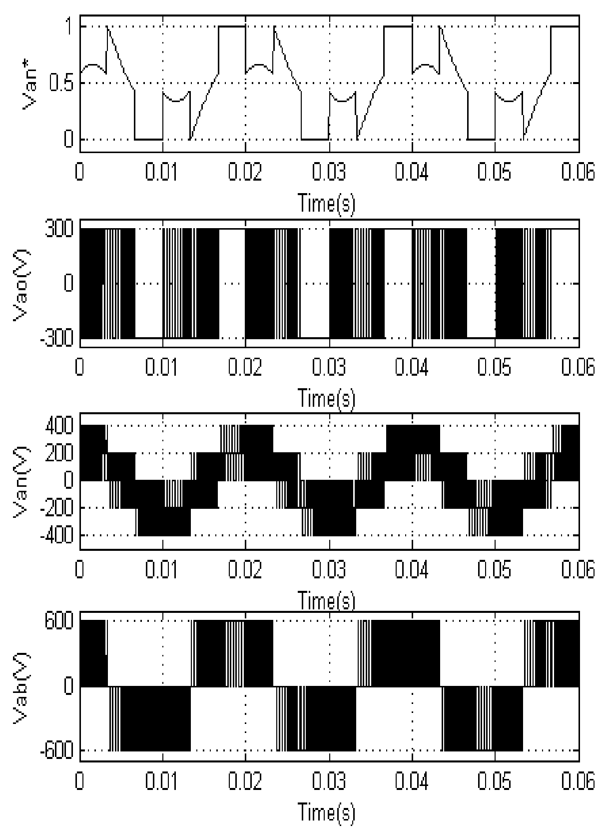


Fig. 6 Simulation results of DPWM0 algorithm at modulation index of 0.6

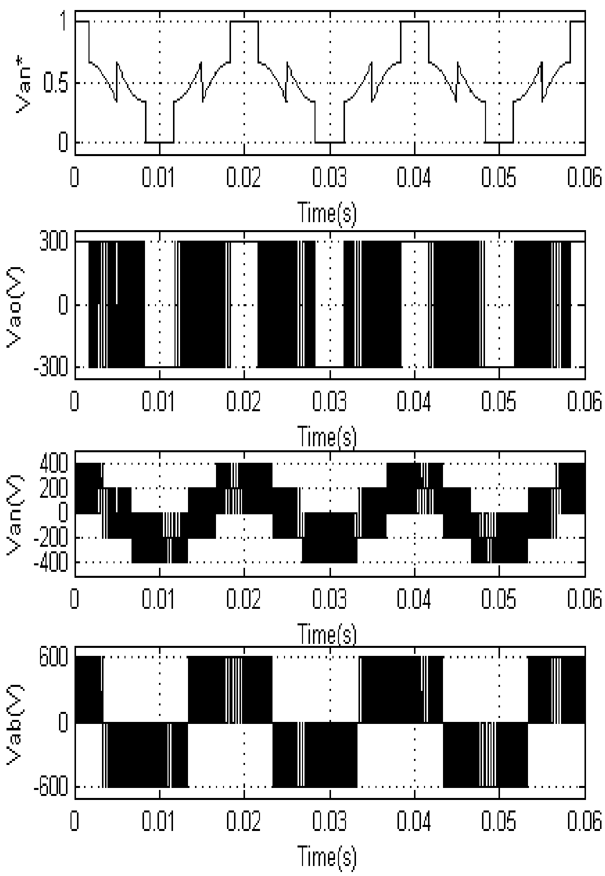


Fig. 7 Simulation results of DPWM1 algorithm at modulation index of 0.6

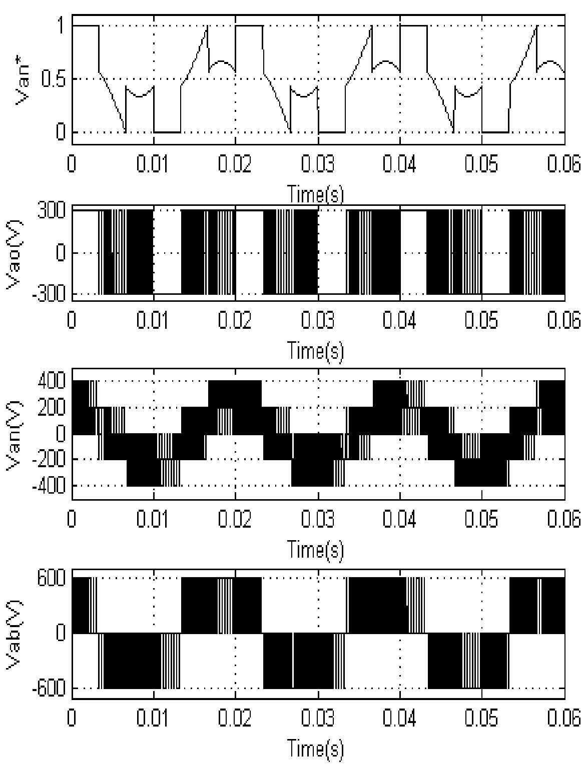


Fig. 8 Simulation results of DPWM2 algorithm at modulation index of 0.6

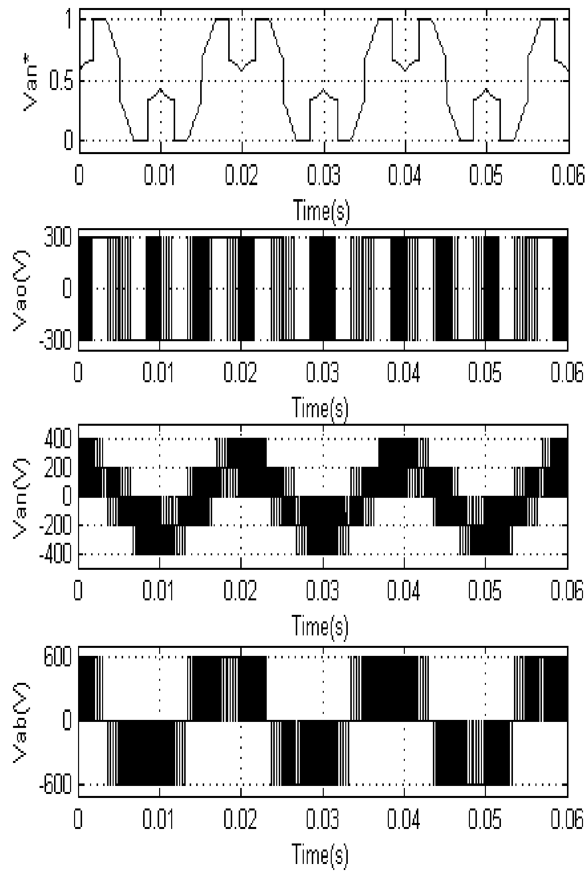


Fig. 9 Simulation results of DPWM3 algorithm at modulation index of 0.6

From the above simulation results, it can be concluded that as the SVPWM algorithm is a continuous PWM algorithm, it gives continuous pulse pattern and more switching losses. Whereas, the DPWM algorithms clamp each phase to either positive or negative DC bus for 120 degrees over a fundamental cycle, which reduces the switching frequency and switching losses by 33.33% when compared with the SVPWM algorithm. Thus, the proposed GPWM algorithm generates a wide range of PWM algorithms at linear modulation indices with reduced complexity.

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