A NOVEL APPROACH TOWARDS SIX-STEP OPERATION IN OVERMODULATION REGION IN SVPWM VSI

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ABSTRACT

Over modulation switching enables the operation of an inverter beyond the normal region, unto the six-step range. As volt-sec compensation is not possible in every sampling period, it is achieved in every sector of operation in overmodulation. The approach presented here segregates the OVM switching into two modes namely, Mode-I and Mode-II. In Mode-I, the required fundamental volt-sec compensation is obtained in every sector by reducing the switching times of the zero voltage vectors and a proportionate increase in the switching times of the active voltage vectors. This process continues until the modulation index of 0.977 beyond which the zero vector switching region is exhausted. In Mode-II, a systematic pattern of switching is proposed, that gets modified with the increasing modulation index. Such switching patterns minimize switching on one hand and give a better harmonic spectrum on the other. The operation of the extended range of mode I and the smooth transition into mode II and six-step is verified using simulation results.

Keywords: over modulation, harmonic distortion, volt–sec compensation.

INTRODUCTION

Implementations of various PWM techniques have been a major area of research. Latest of them is space vector modulation technique. The basic advantage of SVPWM is that it increases the linear range of operation till 0.907 unlike the conventional sine PWM method having linear range till 0.785. The concept of operation of linear or non-linear region is based on modulation index that indirectly provides information about the inverter utilization capability. . This feature of SVPWM puts on edge over other PWM techniques. Till MI $\leq$ 0.907 SVPWM inverter operates in the linear region meaning whereby that the modulation index is directly proportional to the fundamental component of the line side voltage. Beyond MI = 0.907 SVPWM inverter stands operating in the non-linear or in other words overmodulation region. This overmodulation region is further divided into two zones. Zone 1 lies between $0.907 < MI \leq 0.9535$ and zone II lies between $0.9535 < MI \leq 1.0$.

The main aim of any PWM technique is to utilize the inverter to its full capacity that is achieved only with six-step operation. In six-step operation, maximum value of the desired voltage vector is obtained. In SVPWM, the operation from under modulation to overmodulation finally leads to the above-mentioned fact i.e. to achieve a six-step operation. Till now the SVPWM and its overmodulation strategy have been studied using voltage vector [1,3] and current dynamics [2] for high performance ac drive system. Fourier series expansion of the waveform of the phase voltage reference is proposed as a new overmodulation strategy in [3].

Over modulation algorithm is proposed for low switching frequency PWM application again taking relationship between controls variable and fundamental voltage based on number of pulses [4]. In addition, Bolognani and Zigliotto have suggested a strategy for smooth transition from overmodulation to six-step operation of SVM inverters in [5]. A classification algorithm developed by A.R. Bakashai et al in [6] also aid in achieving a smooth transition from overmodulation to square wave operation without any approximation. Currently, a few of the researchers [7,8] have developed a new strategy of controlling Induction motor using SVPWM by taking directly stator flux error as the ref. value replacing the voltage vector. Some of the researchers [9,10] have gone to the extent of proposing new strategies in over modulation Zone II with the modification in the formulae of calculating the continuous switching of a single voltage vector. None of the above-mentioned researchers has considered the extension of the range of either of the zones of operation.

Contribution and organization of the paper

According to Faraday's law of electromagnetic induction (neglecting stator resistance), $Vs = \frac{d\Psi s}{dt}$ and in discreet form this can be written as $Vs \cdot Ts = \Delta\Psi s$. Hence, it is seen that the requisite change in stator flux vector can be achieved through the application of the voltage vector for a specific duration.

The proposed strategy of extending the range of overmodulation zone I and further achieving a smooth transition to overmodulation II and six step, considers the instantaneous value of stator voltage vector. The gating pattern is generated by the sampled error between the reference voltage vector and the estimated or actual voltage vector. Consideration of stator voltage vector error as the commanded value helps to achieve zero flux vector error in a fundamental cycle for all operating angular velocities as in [8].

The achievement of the increased MI for zone I overmodulation, carried out right from the fundamental principle of calculating the switching times and selection

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of switching states is discussed in this paper. The mathematical equations developed are simulated through MATLAB / SIMULINK.

SPACE VECTOR MODULATION TECHNIQUE

Figure-1 shows the three modes of operation of SVPWM. The operation within the inscribed circle of the regular hexagon is the linear region while operation outside the inscribed circle until the circumscribed circle around the hexagon depicts overmodulation region.

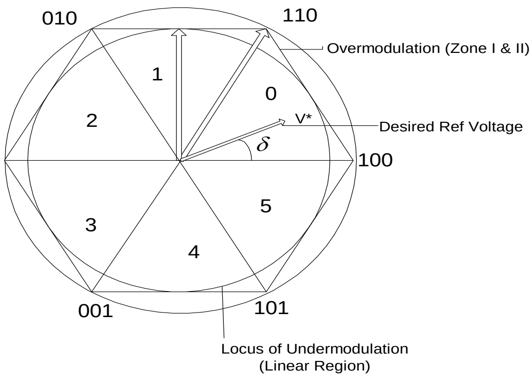

Figure-1. Three modes of operation of SVPWM.

At the end of the liner modulation i.e. at a MI of 0.907, the reference voltage vector tip traces a circle whose radius becomes greater than that of the inscribed circle of the hexagon representing the voltage vectors that can be applied in the six sectors.

OVERMODULATION (ZONE I)

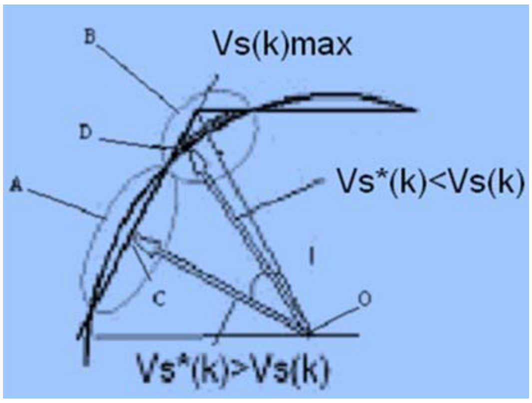

Figure-2

As can be seen from the Figure-2,

OB = Vs (k) $_{max}$ (maximum available voltage vector in a sector), OD = Vs*(k) (desired voltage vector also called the reference voltage) and OC = 0.866* Vs(k)$_{max}$ (maximum voltage vector available in the linear region of modulation).

The whole situation in the OVM I stage can be divided into two regions A & B. The value of the reference voltage vector i.e. Vs*(k) = OD is more than that available i.e. OC, in region A. In region B, the reference voltage vector Vs*(k) is less than the available voltage vector (whose maximum value is Vs(k)$_{max}$). In region A, maximum loss of voltage occurs when the desired reference vector is at 30 degrees and the available voltage vector is only OC= 0.866* Vs (k) $_{max}$ so

Max loss at this angle = Vs*(k)-0.866* Vs(k)max (1)

For the switching times τau_a, τau_b, and τau_0, τau_0 becomes negative in region A, which otherwise is not possible practically, so τau_0 is taken to be equal to zero and the switching is obtained by applying active states for τau_a and τau_b period only. The voltage vector in this region thus moves along the hexagon till the boundary of the region B starts.

In the region B, there is an ample reference vector magnitude to accommodate the τau_0 so all three switching times are applied albeit in a modified manner. The loss of angular velocity in the region A is compensated in the region B. This compensation results in the modification of the switching times.

The rationale of the proposed method lies in the fact that since negative values of τau_0 are not possible to achieve in the region A, the value of τau_0 is kept zero in this region and only the two active voltage vectors are switched. The accompanying loss in the volt-seconds has to be compensated. This is done in the region B where the values of τau_a & τau_b have to be increased by applying the factor Kc, which is decided by equating the maximum loss (of volt-sec) in the region A with the maximum possible value of compensation that can be provided in the region B. Thus the average angular velocity can be made equal to the desired (reference) value in a sector rather than that in a complete cycle. It has been found that the modulation index at which negative values of τau_0 start occurring (during simulation) is the value at and beyond which compensation for the loss of volt-sec in the region A cannot be done.

The modified switching times are

τau_a1 = τau_a + 0.5 K_C τau_0
τau_b1 = τau_b + 0.5K_C τau_0
τau_01 = τau_s – τau_a1 – τau_b1 (2)

Where K_C is a compensation factor which decides what percentage of the maximum voltage vector ought to be required to compensate for the loss of angular velocity in the region A.

In the literature reported thus far [9], the end of over modulation region I happens at a modulation index of 0.9535 after which over modulation II sets in which comprises of a continuous application of a particular voltage vector to achieve a particular value of angular velocity of the voltage vector.

The simulated results with the above switching times in equations (2) show that the overmodulation I region persists beyond the above reported modulation index and it gets stretched till 0.977. This is an extension of around 2.35 % which is a significant improvement.

OVERMODULATION (ZONE II)

In the overmodulation Zone II region, the time till which a continuous application of a particular voltage vector is done, is the duration till when due to absence of switching, the control feature is lost. This keeps on increasing with the increased velocity demand. During this period, any one vector is held for a certain time. Zone II uses the concept of continuous application of a particular voltage vector in order to achieve the desired average voltage vector and hence angular velocity. The operation in Zone II finally leads to the achievement of six-step output voltage. At six-step stage, the control on the angular velocity is lost but maximum value of the voltage is available giving a fixed but maximum angular velocity.

RESULTS AND DISCUSSIONS

The simulated results using MATLAB/SIMULINK are given in Figures 3, 4 and 5 where typical values of MI = 0.9535, 0.97 and 0.99 are considered respectively, for showing the difference in the various waveforms from the usual limit of over modulation Zone I i.e. MI = 0.9535.

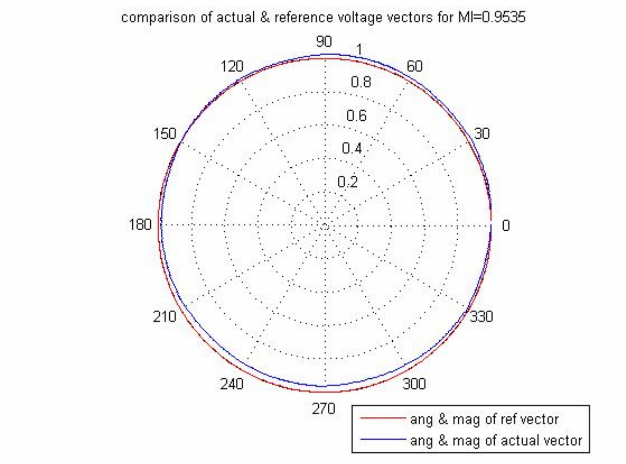

Figure-3(a)

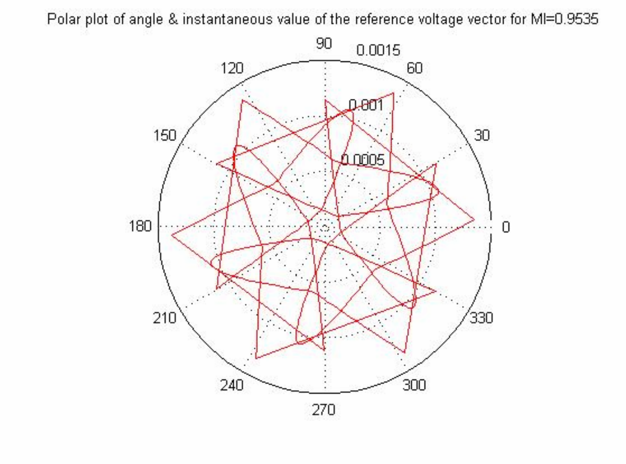

Figure-3(b)

In the above simulations the switching frequency has been taken as 20 KHz and the modulating frequency (or the frequency which is that of the fundamental component of the inverter output voltage waveform) is 50 Hz. Thus the normalized value of the voltage vector will be given by:

Vs (normalized) = [(2*pi*50)/20000] = 0.0157. So long as the value of the reference voltage vector locus does not cross the 0.0157 mark (as is shown in figs 3(b) for MI = 0.9535 and 4(b) for MI = 0.97), the compensation is possible and the overmodulation region I is said to exist.

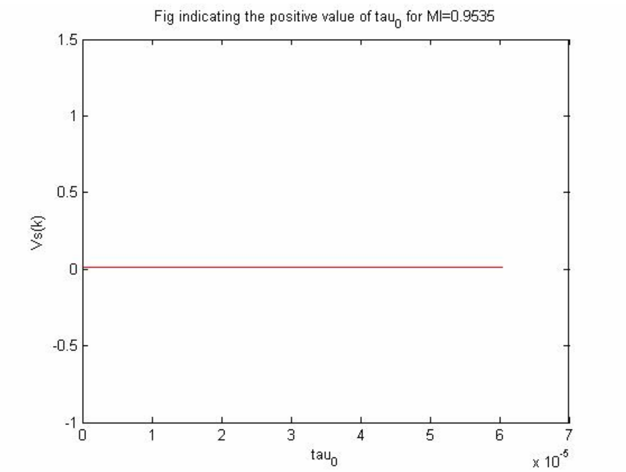

Figure-3(c)

The plots of various parameters are shown in Figures 3(a, b and c) for MI = 0.9535, which is the existing reported value of MI where overmodulation region I terminates and thus this MI value demarcates over modulation zone I and zone II. Figure 3(a) proves that the actual value of voltage vector strictly tries to follow the reference voltage vector and through the compensation the areas can become equal. The same is depicted for MI = 0.97 in Figure-4(a) where the maximum loss in actual voltage vector is successfully compensated by the maximum available voltage vector at the vertices of the hexagon. The same control and compensation is not possible for MI = 0.99 as is clear from Figure-5(a). Here, clearly overmodulation Zone II exists and a continuous switching of a single voltage vector control technique is adopted to finally reach to six-step voltage level.

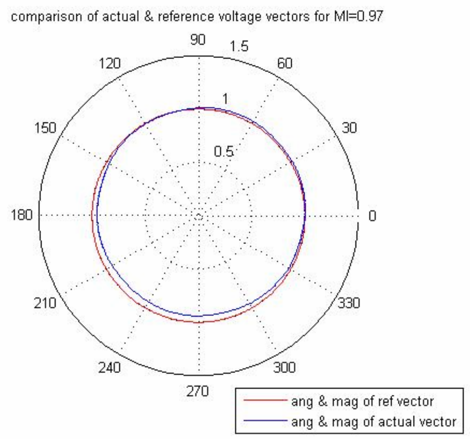

Figure-4(a)

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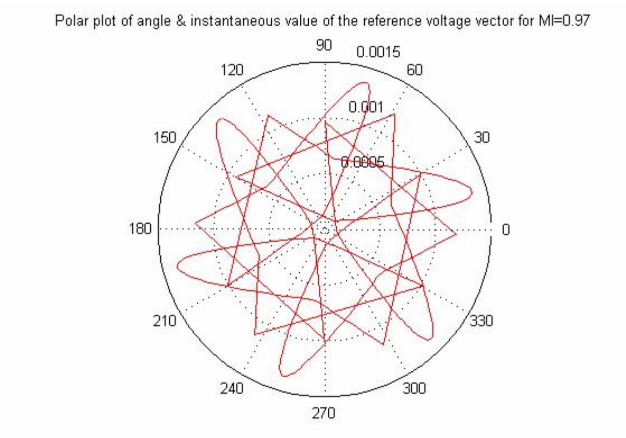

Figure-4(b)

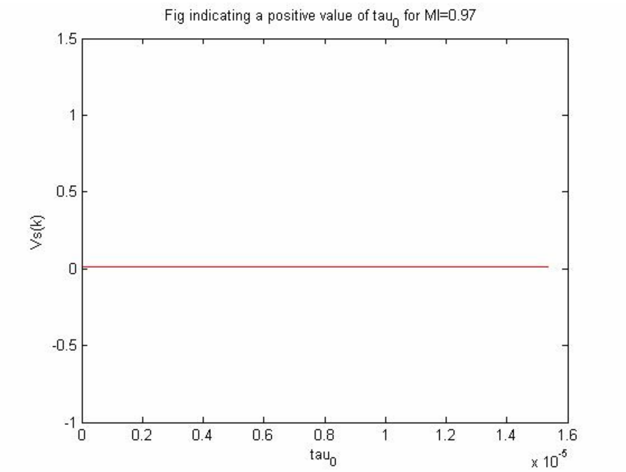

Figure-4(c)

Figures 4(a, b and c) show the plots of same parameters considered in Figure-3 but for MI = 0.97. Figure-3(b) and Figure-4(b) reflect the difference in value of magnitude of reference voltage vector. The increased value of the normalized voltage vector in Figure-4(b) is still within the range (0.0157) where compensation is possible, whereas in Figure-5(b) for MI = 0.99 the magnitude of voltage vector crosses the boundary of the desired value and thus loses control through compensation process.

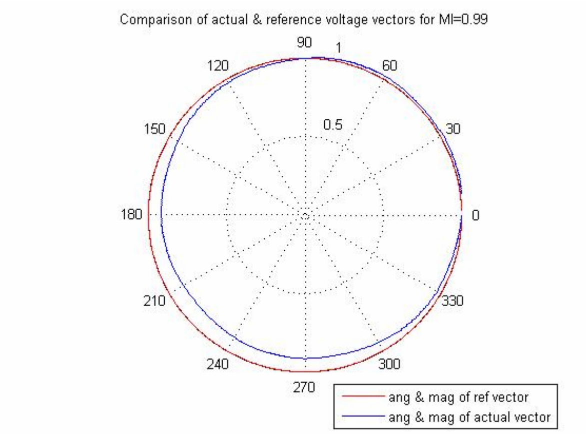

Figure-5(a)

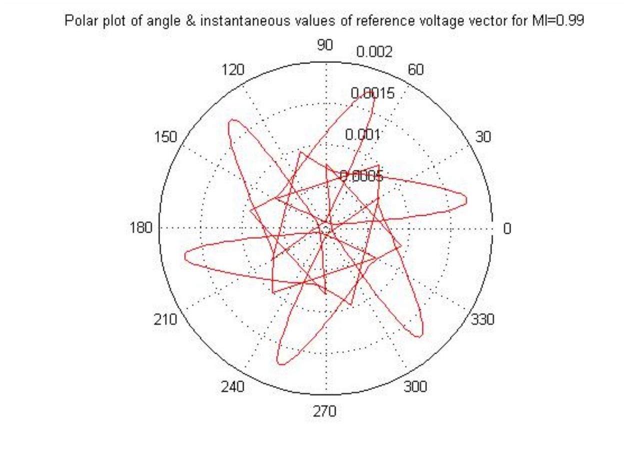

Figure-5(b)

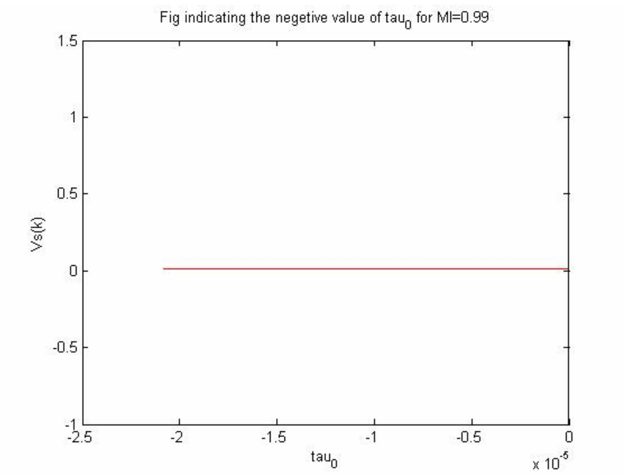

Figure-5(c)

The waveforms of various parameters for MI = 0.99 are given in Figures 5(a, b and c). As seen from Figure-5(c) which is the plot between τau_0 and Vs(k), the value of τau_0 becomes negative, unlike in Figure-3(c) and Figure-4(c) where the values of τau_0 are positive. The negative values of τau_0 directly reflect the zone of operation in over modulation II region in SVPWM inverter. Since τau_0 cannot be negative so is kept zero and the control is achieved through a continuous application of the active state vectors. Thus, the overmodulation zone II operation starts. The simulated results in Figures 3(c), 4(c) and 5(c) define and conclude the extended range of operation of Zone I in overmodulation region.

A smoother control of torque and speed of three-phase induction motor is easily possible now with extended range of overmodulation Zone I. This gives greater flexibility in obtaining the required input voltage of the motor from the SVPWM inverter by generating the gating signals accordingly. It also helps in a better and smooth transition from overmodulation to six step operation.

CONCLUSIONS

The novel approach towards the achievement of extended range of Zone I overmodulation presented in this paper when realized through simulations show the improved transient response of the induction motor with less effect of non linearity faced during overmodulation operation in SVPWM inverter. Since the Zone I range is stretched beyond the existing value of MI = 0.9535, this in turn, automatically reduces the range of operation in Zone II i.e. now Zone II region starts at a much later value of MI i.e. 0.977. Hence, the control and transition to six-step operation of the required voltage vector is easier and even. Thus the proposed approach removes the problem arising out of the extreme non-linearity starting with the advent of overmodulation zone II by increasing the range of operation of zone I.

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