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Performance analysis of different PWM techniques on V/f-based speed control with adjustable boost voltage application for induction motors

Asenkron motorlar için ayarlanabilir gerilim uygulamalı V/f tabanlı hız denetiminde farklı PWM tekniklerinin performans analizi

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Abstract

This paper presents a comparative study and a method to improve Volt-Hertz (V/f) based speed control of Induction Motors (IMs). For this purpose, Sinusoidal Pulse Width Modulation (SPWM) and space vector pulse width modulation (SVPWM) techniques are investigated and evaluated, especially from the point of their control performance on the V/f-based control for three-phase IMs working at different load and speed conditions. From this aspect, it is a different study from the literature. Steady and transient effects of both techniques on the above mentioned control methods are analyzed for several case studies. Afterwards, adjustable boost voltage application with modified reference commands technique is proposed for both PWM methods in order to improve start-up performance. All investigations for both PWM models are carried out under the same conditions. Although SVPWM technique gives more effective results in many cases, the proposed method provides noticeable improvements on SPWM-based applications from point of performance on the control method. As a novelty of this study, it is shown that, the bad performance of the control method at low frequency in SPWM application, which has lower computational burden for low cost microcontroller, can be improved by applying adjustable boost voltage along with modified references that are proportional to the DC bus current.

Keywords: Induction motor, Performance analysis, Pulse width modulation, Variable speed drives, Volt-Hertz control

Öz

Bu makale, Asenkron Motorlarının (IM veya ASM) Volt-Hertz (V/f) tabanlı hız kontrolünü iyileştirmek için bir yöntem ve karşılaştırmalı bir çalışma sunmaktadır. Bu amaçla, özellikle farklı yük ve hız koşullarında çalışan üç fazlı asenkron motorların V/f tabanlı hız kontrol performansı açısından sinüzoidal darbe genişlik modülasyonu (SPWM) ve uzay vektör darbe genişliği modülasyonu (SVPWM) teknikleri incelenip değerlendirilmiştir. Bu bakımdan, literatürden farklı bir çalışmadır. Her iki tekniğin yukarıda belirtilen kontrol yöntemi üzerindeki kararlı ve geçici hal etkileri çeşitli örnek durumlar üzerinde analiz edilmiştir. Daha sonra, kalkış performansını artırmak için her iki PWM yönteminde de düzeltilmiş referans komut tekniğine eşlik eden ayarlanabilir yükseltici gerilim uygulaması önerilmiştir. Her iki PWM modeli için yapılan tüm araştırmalar aynı koşullar altında gerçekleştirilmiştir. SVPWM tekniği birçok durumda daha etkin sonuçlar vermesine rağmen, kontrol yöntemi üzerindeki performans açısından SPWM tabanlı uygulamalarda önerilen yöntem dikkate değer iyileştirmeler sağlamaktadır. Bu çalışmanın bir yeniliği olarak, düşük maliyetli mikrodenetleyici için daha az hesaplama yükü olan SPWM uygulamasında karşılaşılan düşük frekansta kötü kontrol performansı, DC hat akımına göre oransal olarak değişen düzeltilmiş referans komutlarıyla birlikte uygulanan ayarlanabilir yükseltici gerilim yöntemi ile iyileştirilebileceği gösterilmiştir.

Anahtar kelimeler: Asenkron motor, Performans analizi, Darbe genişlik modülasyonu, Değişken hızlı sürücüler, Volt-Hertz kontrol

Introduction

The extensive use of Inductions Motors (IMs) is generally associated with the simplicity of its structure, low cost in acquisition and maintenance. One of the control methods to be applied easily on IMs has been exceptional among the others in recent years, which is called constant V/f-based scalar speed control, especially for fans and pumps being used in industry, thanks to the introduction of solid-state inverters. That's why the theory of the method has been well investigated and accepted as a conventional control method [1]-[3]. Also, lots of application notes, papers and textbooks are available for the understanding of the fundamentals of this method and its drawbacks together with different solutions supported by vector and artificial intelligence (AI) techniques [4]-[10].

On the other hand, pulse width modulation (PWM) techniques used in drive systems, in which low-switching-frequency that is controlled by medium-voltage high-power industrial ac drives are employed and have an importance on the compromising the harmonic distortion of machine currents, the influence of load-current dependent switching time delay and transients in PWM schemes. Switching losses of the power semi-conductor devices are reduced with the application of low switching frequency, which results the inverter to be more efficient [11],[12]. In recent years, several PWM methods have been proposed in order to obtain a supply with a variable voltage and a variable frequency for torque and speed control of IMs. The most widely used PWM techniques among those are sinusoidal PWM (SPWM), space vector PWM (SVPWM) and hysteresis band PWM (HBPWM). Most of the other PWM techniques are based on derivations of regular PWM and the conventional techniques mentioned above, to enhance the performance of the control method. A comparison study on inverter losses with SPWM, SVPWM, and discontinuous PWM (DPWM) was presented by Wu et al. [13]. In this paper, the prediction of inverter losses with different conditions of modulation index, gate resistance, and switching frequency for all mentioned PWM methods were investigated. Kumar et al. [14] proposed asymmetric SVPWM technique using additional voltage sectors' switching states, which is determined by a state transition matrix to minimize switching losses of inverter and provide stability of the IM. Edpuganti et al. [15] studied on synchronous optimal pulse width modulation because this method allows to use low switching frequency modulation without affecting the total harmonic distortion (THD) for the inverters of medium-voltage high-power applications. As emphasized in ref [16], the main purpose is to minimize both the switching losses in the inverter and the harmonic distortions of the stator currents and the torque.

In ref [17], an advanced hybrid PWM technique was proposed to reduce torque ripples in IM drives by using advanced bus-clamping switching sequences, which apply an active vector twice in a subcycle. Reddy et al. [18] reports that torque pulsation is strongly influenced by the PWM technique used, especially in open loop V/f controlled IM, and they conclude that hybrid PWM shows better reduction in torque ripples when compared with conventional SVPWM technique. Also, space vector based hybrid PWM techniques involving multiple sequences were introduced by Narayanan et al. [19] and Das et al. [20] for reducing current ripples at high line voltages. They reported that hybrid PWM notable reduces the THD at low and high-speed ranges of a constant V/f controlled IM drive, when compared to centered SVPWM [19],[20].

A new set of Bus Clamping Pulse Width Modulation (BCPWM), dealing with a special type of switching sequences to reduce the harmonic distortion in the line currents, over conventional SVPWM for V/f controlled IM were proposed by Praveena et al. [21]. On the other hand, generalized direct modulation control methods improve the output voltage up to 78.86% of input voltage in matrix converter for speed control of IM. By these switching strategies, the balanced and unbalanced output voltages are generated by any set of balanced and unbalanced input voltages [22],[23].

Triangle comparison versus space vector based PWM was well studied for inverter fed drives and space vector based approaches were highlighted from point of significant drive performance [24],[25]. In a survey study [26], single pulse modulation, multiple pulse modulation, and space vector based approaches were investigated by simulations and implementations to better comprehend these modulation techniques. Relationship between these PWM techniques is brought out [27]-[29]. In ref [30], modified SVPWM was proposed to improve the THD for high power inverter applications leading to self-balancing of the direct current bus capacitor voltages. A comparison of common-mode voltage PWM method with standard PWM methods was introduced for three-phase voltage-source inverters and the application of appropriate PWM methods was presented by Hava et al. [31]. Also, simulation and comparison of SPWM and SVPWM were carried out for three-phase inverters, by concluding that the DC bus voltage efficiency was better in SVPWM [32],[33]. But, SPWM with high quality factors and cleaner harmonic spectra was perceived to be the best solutions by Profumo et al. [34]. But, many researchers report that SVPWM is more available for vector-based torque and speed control methods than the other PWM techniques because of its easily adjustable amplitude and independent replacement of reference voltage vector in every switching period, especially, the application of this method in matrix converter has been exceptional among the others [35]. However, concept of modulation index which, is defined by different parameters for the both PWM techniques is highly effective on the control outputs of the system and the harmonics [36],[37].

Although SVPWM has some disadvantages of computational burden and switching losses [38], it provides a better performance, when compared with the SPWM or commonly used PWM techniques. Implementation of SVPWM was realized to be simpler and faster than conventional ones and the computational burden has been reduced by a low cost microcontroller or an improved computing process by advanced microchip embedded vector control based method [39],[40]. On the other hand, in order to generate the desired output voltage for single or three-phase inverters by a different PWM techniques, which has controllable average voltage, the duty cycles of each of the switches have been adjusted. Thus, the desired unbalanced and balanced output voltage generating is possible [41],[42].

Performance of the IM with a full load torque controlled by constant V/f-based method with different PWM techniques was introduced by El-Saady et al. [43], in terms of THD, harmonics spectra, utilization of supply voltage, fundamental peak of the output voltage and motor speed. However, the dynamic performance of IM using SPWM under reference speed and load torque variations was not investigated in that study. Besides, start-up performance, settling time error and oscillations in steady state were not analyzed. In particular, at low speeds, for getting acceptable improvements in V/f-based speed control of IMs, estimation of the true value of the stator resistance is needed [44],[45]. But, the proposed method did not aim at coping with minimization of steady state error and quick response of control system [45]. To make zero the steady-state error in IM drive system using V/f control, a method was introduced in ref [46], and the authors called the method as frequency compensation control (FCC). In FCC, while the steady-state speed error was minimized, the problem emanating from torque requirements at low speed was not investigated. But, stator voltage oriented methods were reported to have achieved great improvements on V/f-based control at low speeds, especially by improving the load capability at low frequency and provide fast response to the system [47],[48].

One of the studies dealing with all of the problems postulated that auto-boost voltage compensation for the voltage, drop across stator leakage impedance and that, slip frequency compensation was needed to improve V/f control performance both at low speed and steady-state operation [49]. But, the effects of the adaptive boost voltage application on performance improvement of V/f speed control and modification of the reference command just as in frequency compensation method for keeping actual reference have never been analyzed and discussed in the literature, for all operational cases from point of using different PWM techniques. Boosted torque requirements at start-up and the ability of following the reference command in case of any change in the operation conditions are of high importance for open-loop constant V/f-based controlled IM. Therefore, this paper purposes to present an investigated study on the control performance of V/f-based control for IMs operating under variable speed and load conditions in case of using different PWM techniques that are selected as SPWM and SVPWM for the investigation. Afterwards, to achieve noticeable improvement in evaluation criteria, such as good start-up performance, short settling time, low steady-state error and low oscillation in steady state, the application of adjustable or adaptive boost voltage with respect to the DC bus current together with the modified reference command method is proposed, and good the achievements of these criteria are discussed in subsequent sections. In this study, some information being well-known in literature, such as dynamic model of the machine, internal structure of the voltage sourced inverter model and some template relations about SPWM technique are especially not given to attract attention to essence of the study.

1 Fundamentals of V/f-based control method

V/f-based variable speed drives are generally used in low performance applications, where the precise speed control is not necessary. The voltage at each frequency is adjusted by keeping the V/f constant up to base speed. After reaching the base speed, full voltage is applied. The torque-speed curves of IM obtained by this method are given in Figure 1. In this method, if the frequency is held at determined constant value, the speed drops slightly from no-load (point 1) to full-load (point 2) with the application of full load. This is a normally open loop behavior. However, when the application requires the speed to be held constant precisely, it can be achieved by increasing the frequency so that the full-load operating point moves to point-3 via closed loop speed control techniques because of slip requirement to produce sufficient torque [50].

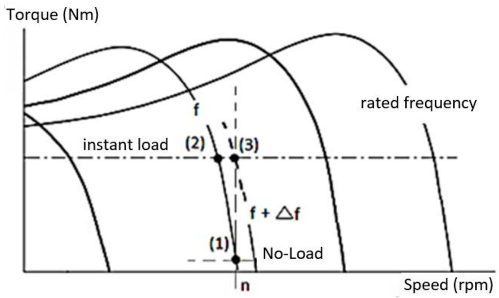


Figure 1: Torque-speed curves of an IM at different frequencies.

An open-loop speed control system scheme for V/f-based speed control of IM is illustrated for the both PWM models in Figure 2. The V/f should be kept constant to avoid the air gap flux variations and to meet constant electromagnetic torque requirements. Updating fundamental frequency to obtain desired mechanical output speed, the *rms* value of the first term of output voltage is adjusted according to constant V/f. On the other hand, when the output voltage is increased without frequency adjustment, the IM can operate in the flux saturation region or with a weakened field. Besides, the ratio of V/f can be adjusted to a bigger value to meet the load torque at start-up, while considering that higher V/f will lead to a condition that is highly disadvantageous. However, the application of this method at low frequency has bad performance, due to the influence of the stator resistance and the necessary rotor slip that produce electromagnetic torque. In addition, the air-gap flux decreases if frequency increases more than rated frequency [51].

It is well known phenomenon, that while the frequency increases, the applied voltage needs to be increase in order to keep the air-gap flux constant, but not let it saturate. The magnitude of air-gap flux is approximately proportional to the ratio of voltage to frequency as follows:

$$\Phi_m \approx \frac{V_{ph}}{f_s} \quad (1)$$

Where, Φ_m is magnitude of air gap flux, f_s is supply frequency, and Vph is phase voltage.

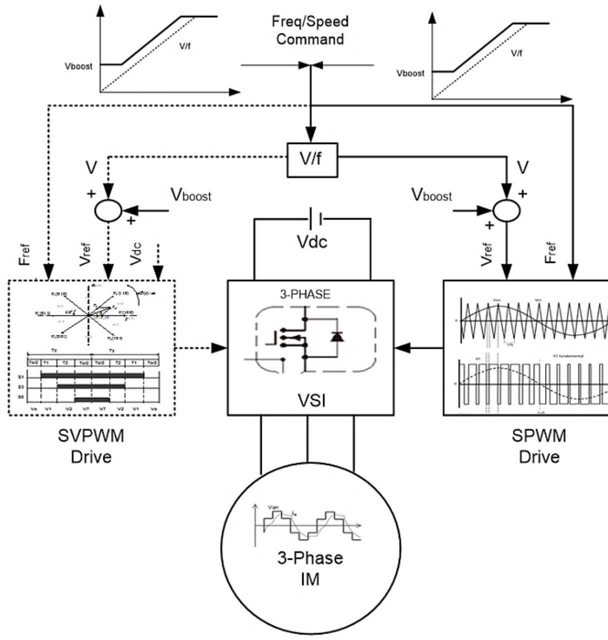


Figure 2: V/f-based open-loop speed control scheme for driving both PWM methods.

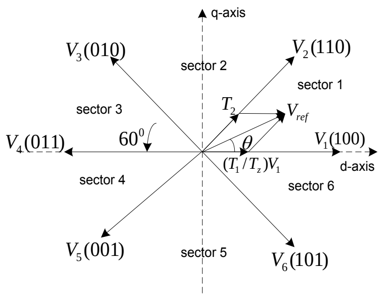
2 Principles of the PWM techniques investigated

Voltage source inverter (VSI), in which the DC bus voltage is constant, consists of two switches with an integral inverse diode per phase. The effective value of the phase voltage can be adjusted, and its harmonics amplitudes together with orders are reduced by using different PWM techniques. In motor control application, the most common PWM approaches are SPWM and SVPWM techniques. While the rms value of the first term of output voltage in SPWM-based inverter is limited to 0.355 times Vdc, space vector modulation method improves this value up to 0.408 times Vdc [52]. SPWM technique is commonly used for the application of scalar speed control methods.

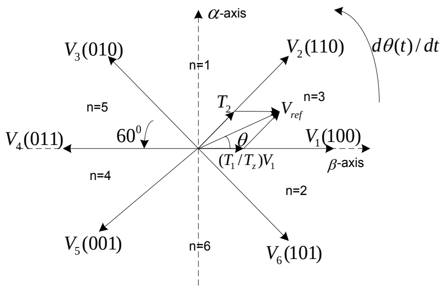
The first technique that was investigated in this study is SPWM. In order to generate any SPWM signal, a carrier signal at desired high frequency, which is a triangular wave that controls the switching frequency, is compared with a sinusoidal signal, which is called reference or control signal. The reference signal is at fundamental frequency that determines the inverter output frequency. When the instantaneous value of the sine reference is larger than the triangular carrier, the output is at $+Vdc$, and when the reference is less than the carrier, the output is at $-Vdc$. This type of PWM is called as bipolar because the output alternates between plus and minus values of the supply voltage of VSI. To obtain three-pair PWM outputs, three different sinusoidal signals shifted by 120-degree relative to each other are compared with the same carrier signal, which is at high frequency [53].

The modulation factor m_f is defined as the ratio of the frequencies of carrier and reference signals in SPWM. Also, the modulation index m_a is defined as the ratio of the amplitudes of the reference and carrier signals. The frequencies of the harmonics are controlled by m_f. But, increasing m_f increases the switching losses, and the *effective* value of the inverter output voltage at fundamental frequency is determined by the m_a.

The investigated second technique is SVPWM. The SVPWM, giving more voltage output of 15%, minimizes the THD, and reduces PWM loses. The reference voltage ($Vref$) is obtained due to switching states. A space voltage vector is represented in each state. Figure 3 shows all space vectors for possible switching states. Where, $S1$, $S3$ and $S5$ symbols define the upper switches.



(a)



(b)

Figure 3: Basic switching sectors and voltage vectors for SVPWM. (a): at dq -axis, (b): at $\alpha\beta$-axis.

In calculation of the switching time for related voltage vectors, amplitude of the $Vref$ is employed with the bus voltage obtained from rectifier side. Application time of any vector for each sector is expressed as follows:

$$\begin{cases} T_1 = \dfrac{\sqrt{3}T_z|V_{ref}|}{V_{dc}}\left(sin\left(\dfrac{n\pi}{3} - \theta\right)\right) \\ T_2 = \dfrac{\sqrt{3}T_z|V_{ref}|}{V_{dc}}\left(sin\left(\theta - \dfrac{(n-1)\pi}{3}\right)\right) \\ T_0 = T_z - T_1 - T_2 \end{cases} \quad (2)$$

$$\begin{cases} \Delta\theta = 2\pi s f_s \Delta t \\ \Delta t = 2T_z \\ \theta(k+1) = \theta(k) + \Delta\theta \end{cases} \quad (3)$$

Where, the ratio of $Vref$ to DC voltage is employed in calculation of the switching time for the switches as a modulation index. And, n is the new number of the sectors at the $\alpha\beta$-axis, T_z is the half of the period, T_1 and T_2 are the application time of the voltages. θ is the position of the applied voltage vector and it is adjusted by the control frequency in each sampling period. Δt is the period of the generated PWM signal [54].

The relationship between variable switching vector and phase voltage vector is given in equation (4).

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{dc}}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (4)$$

Where, $[a \quad b \quad c]^T$ vector is situation of upper switches of the VSI, a equals to 1 as long as $S1$ is ON, otherwise the value of a equals zero. Also, dq components of the reference voltage vector are written by equation (5) and (6) as follows:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & \dfrac{-1}{2} & \dfrac{-1}{2} \\ 0 & \dfrac{\sqrt{3}}{2} & \dfrac{-\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \quad (5)$$

$$|\bar{V}_{ref}| = \sqrt{{V_d}^2 + {V_q}^2} \quad (6)$$

Getting components of the reference voltage and selecting the n at the $\alpha\beta$-axis can be realized by estimating the sector position of reference voltage vector for tracking induced voltage in windings, as follows:

$$\begin{cases} V_{\alpha\_ref} = V_{ref}\cos\theta \\ V_{\beta\_ref} = V_{ref}\sin\theta \\ V_1 = V_{\alpha\_ref} \\ V_2 = \dfrac{1}{2}\left(\sqrt{3}V_{\alpha\_ref} - V_{\beta\_ref}\right) \\ V_3 = \dfrac{1}{2}\left(-\sqrt{3}V_{\alpha\_ref} - V_{\beta\_ref}\right) \end{cases} \quad (7)$$

The new number of the sectors in the algorithm of the control solution for $\alpha\beta$ -axis can be defined as in Figure 4 and represented as n.

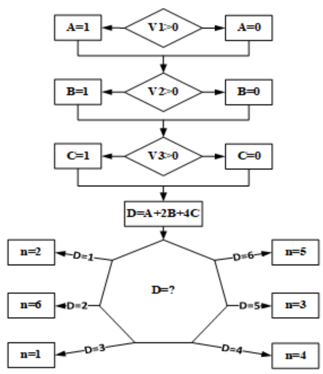


Figure 4: Flowchart to find the number of sectors in the $\alpha\beta$ -axis of the SVPWM.

The reference vector which represents three-phase sinusoidal voltage is generated in SVPWM by switching between the two nearest active vectors and zero vector. In this case, Table 1 takes into account how to calculate the application time for different voltage vectors at each sector [51], [52].

Table 1: Calculation of switching times (Tsx) for each sector.

n	T_{S1}	T_{S3}	T_{S4}
1	$T_1+T_2+T_0/2$	$T_2+T_0/2$	$T_0/2$
2	$T_1+T_0/2$	$T_1+T_2+T_0/2$	$T_0/2$
3	$T_0/2$	$T_1+T_2+T_0/2$	$T_2+T_0/2$
4	$T_0/2$	$T_1+T_0/2$	$T_1+T_2+T_0/2$
5	$T_2+T_0/2$	$T_0/2$	$T_1+T_2+T_0/2$
6	$T_1+T_2+T_0/2$	$T_0/2$	$T_1+T_0/2$

3 Simulation models

All of the simulations are carried out in Matlab/Simulink environments for V/f-based speed control of the IM drives, using SPWM and SVPWM techniques in order to compare the effects of the adjustable boost voltage with modified reference command on the control system performance. The IM used in the models is defined in MATLAB tools as 4 kW, 400 Volt, 50 Hz, and 2-pole pairs. The both PWM based models are explained in detailed in the following subsections.

3.1 Simulink model of SPWM based drive

The Simulink model of a SPWM signal generator is developed to drive VSI and the whole system, and for control of the IM is given in Figure 5. This model consists of three-phase IM, MOSFET power module for VSI, SPWM generator and monitoring blocks. In Figure 5, the reference command is applied independently from frequency and voltage for open loop speed control. Afterwards, reference voltage and frequency command are obtained by depending on the reference command signal, and the reference voltage command can be modified by a boost value for providing sufficient torque at start-up operation under load.

The internal structure of the SPWM generator subsystem is given in Figure 6. Fundamental frequency and modulation index command are applied external inputs for this subsystem model. Output voltage of the VSI is changed by adjusting modulation index, m_a. Because, m_a is also defined as the ratio of peak value of fundamental component of output voltage to the DC bus voltage for the inverter. Therefore, the input reference voltage command needs to change, when, the frequency changes in order to keep constant ratio of V/f. 5-V amplitude of 120-degree phase shifted sinusoidal signals, which have fundamental frequency, are updated by modulation index and placed on 5-V DC threshold. The carrier signal is obtained by square-wave signal generator and integrator block. Thus, 10-V amplitude of the triangular based carrier signal at high frequency is achieved.

3.2 Simulink model of SVPWM based drive

The studied Simulink model of a SVPWM signal generator that is used to drive the VSI for speed control of the IM is given in Figure 7. This model also consists of a three-phase IM, a MOSFET power module. The difference between both models is only a subsystem for SVPWM Generator.

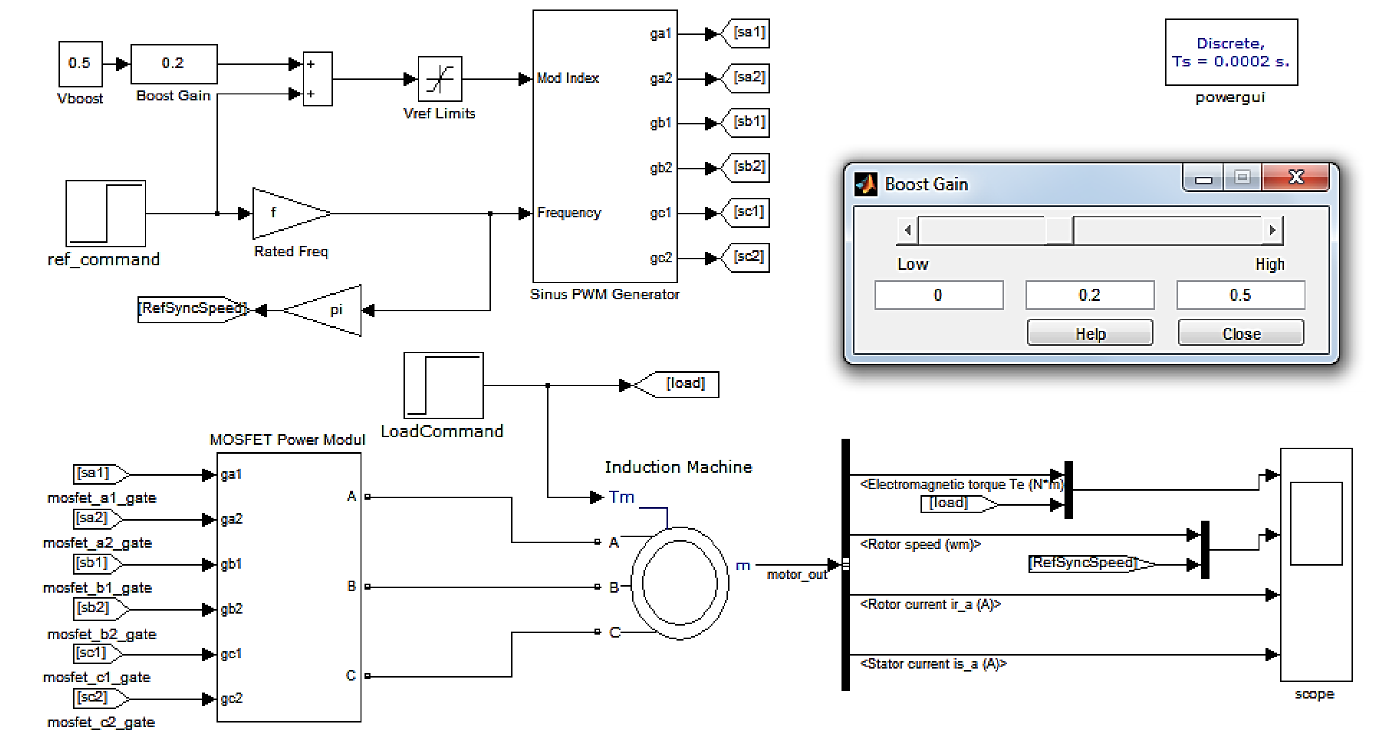


Figure 5: Simulink model of the SPWM-based drive system.

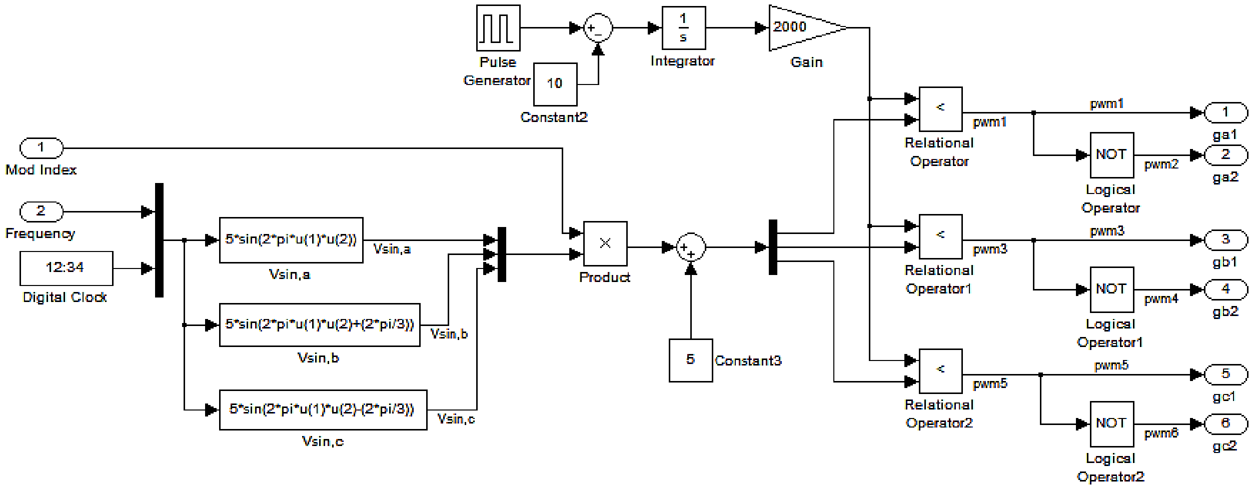


Figure 6: Internal structure of the SPWM generator.

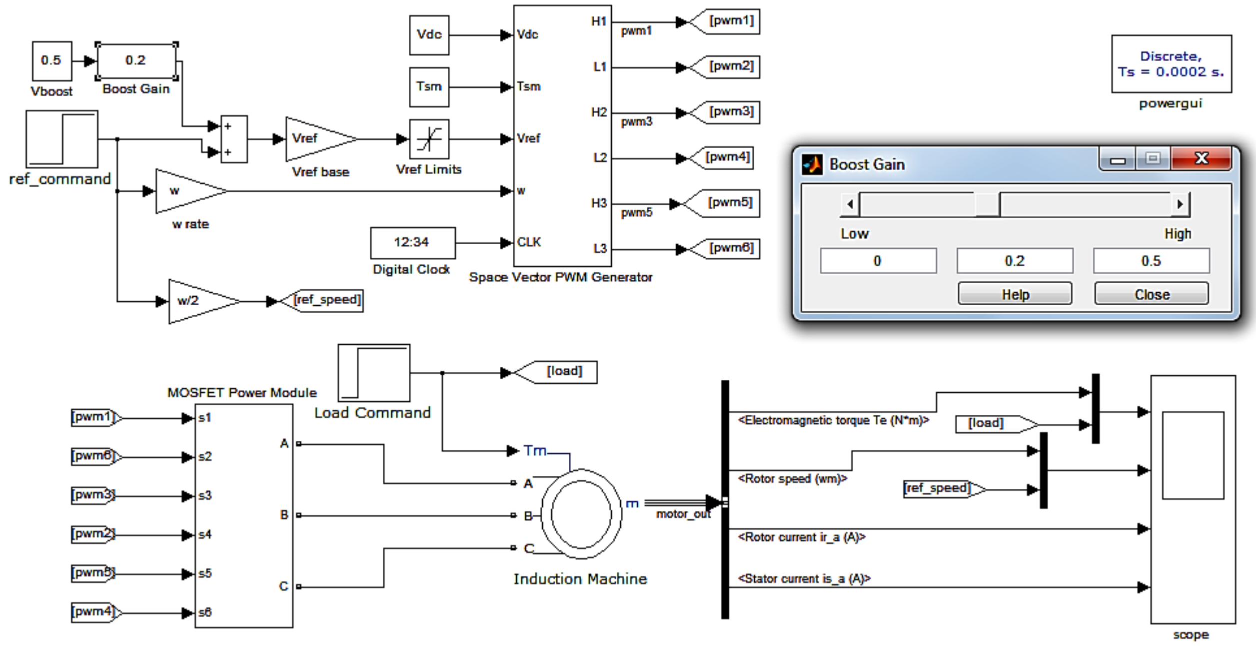


Figure 7: Simulink model of the SVPWM-based drive system.

In Figure 7, the fundamental frequency signal which is an input for SVPWM generator is produced by multiplying with rated frequency. On the other hand, input command of the reference voltage vector is modified by two-third of the rated DC bus voltage and reference command as keeping V/f constant. An adjustable boost value can be added to the modified command voltage signal independent from frequency in order to provide sufficient torque at start-up for the load so as providing stability of speed control.

The open scheme of the SVPWM generator subsystem is given in Figure 8, where T_{sm} is the switching period and it is calculated by the switching frequency, which was earlier defined in model properties. This sub-system model includes a calculator in which space vector switching times are computed at each sector. In both of PWM models, reference voltage command is limited to a maximum value so that over modulation cannot occur.

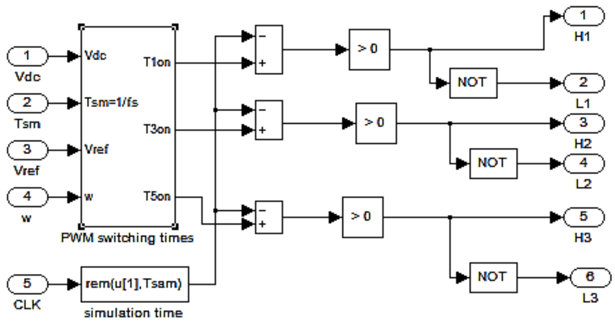


Figure 8: Internal structure of the SVPWM generator.

The subsystem in which switching times of the space voltage vector are computed for determined sector is shown in Figure 9. Durations of T_1, T_2, and T_0 are calculated by the functions, depending on simulation clock, the DC bus voltage, reference voltage command, switching period and fundamental frequency command related to the determined sector. ON-state and OFF-state of the switches are produced in this subsystem by MATLAB logical functions.

4 Simulation studies and results

Steady and transient effects of SPWM and SVPWM techniques on V/f-based scalar control method are compered for several case studies from point of adjustable boost voltage application to improve start-up torque necessity and to provide speed control stability. The modified boost voltage method in both models is investigated and discussed for dynamic behaviors of the system, operation of variable and constant speed control under different load conditions and different reference input commands for open-loop speed control of IM, in detail. All of the tests for the both PWM models are carried out at the same conditions, parameters and commands.

4.1 Case 1: Dynamic behavior of the system

First of all, the dynamic behaviors of the motor driven by the both models for constant V/f-based open loop speed control are investigated under no-load condition, for constant speed command to justify Simulink models accuracy and achieve the dynamics of the system.

Results obtained from this simulation are shown in Figure 10. Where, it is seen that settling time, with reference to the SVPWM model is shorter and the maximum torque produced is higher than SPWM model's, because of output voltage effectiveness of SVPWM. However, steady-state behavior of the system is more stable in SPWM model under no-load condition.

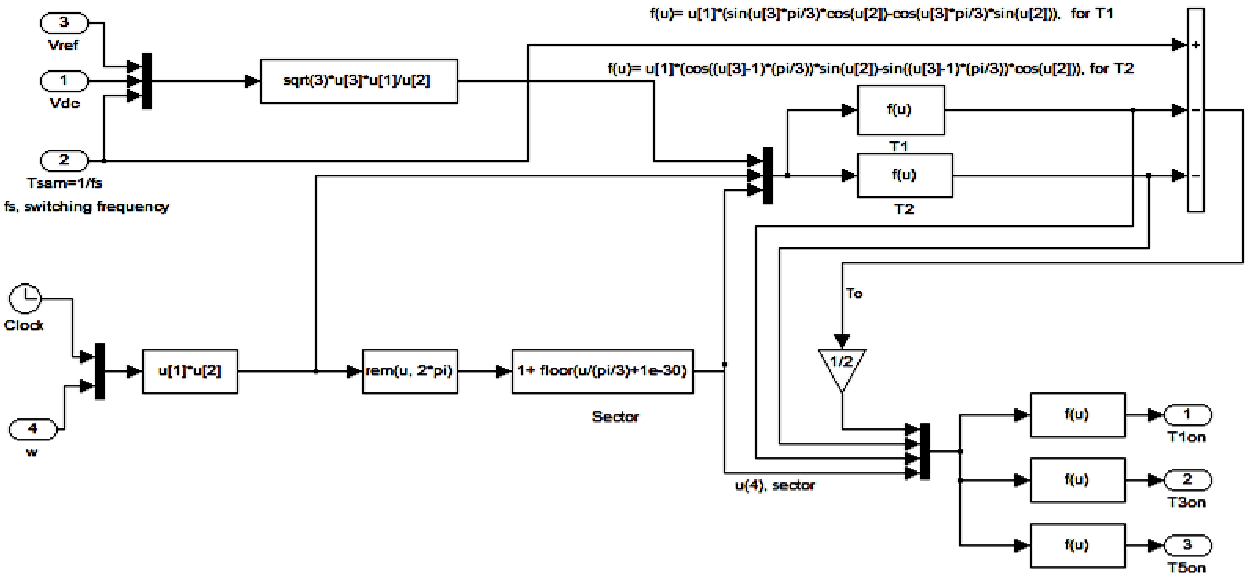
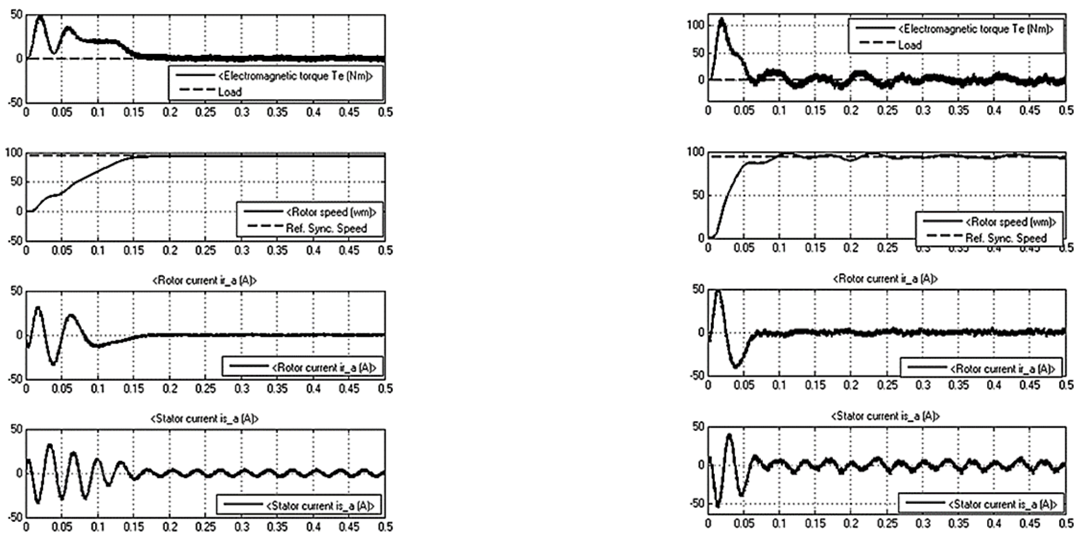


Figure 9: Calculation of SVPWM switching times.



(a) (b)

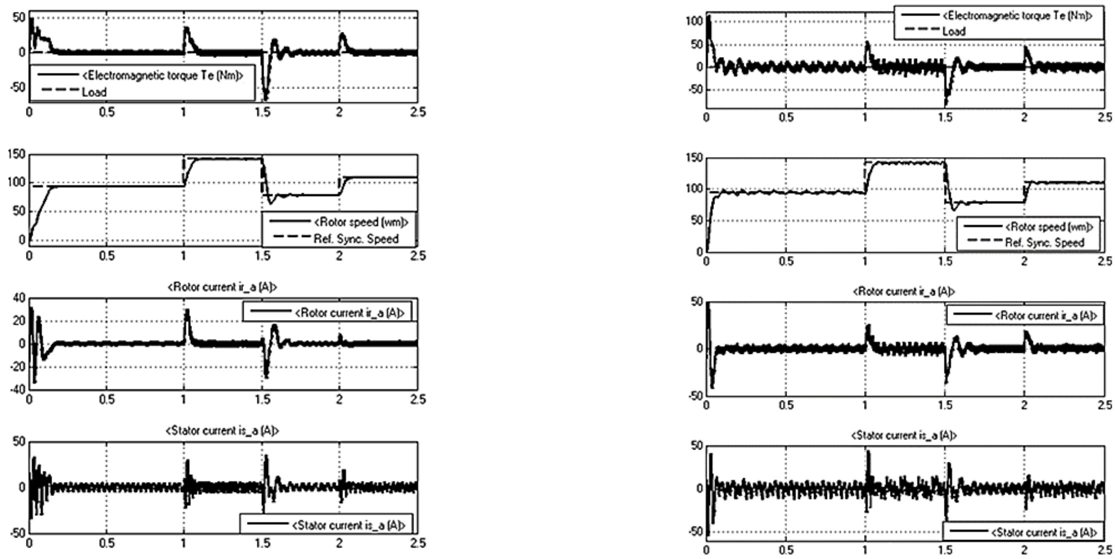
Figure 10: Case 1- Dynamic behaviors under no-load condition for the system driven by SPWM. (a): and SVPWM, (b).

4.2 Case 2: Variable speed operation without load

As depicted in Figure 11, the reference speed command signal in both of PWM models is variable, and mechanical speed closes to the new synchronous point at each command changing because of absence of an external load. The induced torque and current ripples in SVPWM-based drive system are smaller than SPWM ones when the reference speed command changes instantly. But, it can be observed from this figure that there is no obvious distinction on the behavior of the machine in steady-state performance from points of torque, speed and current variations for the both models.

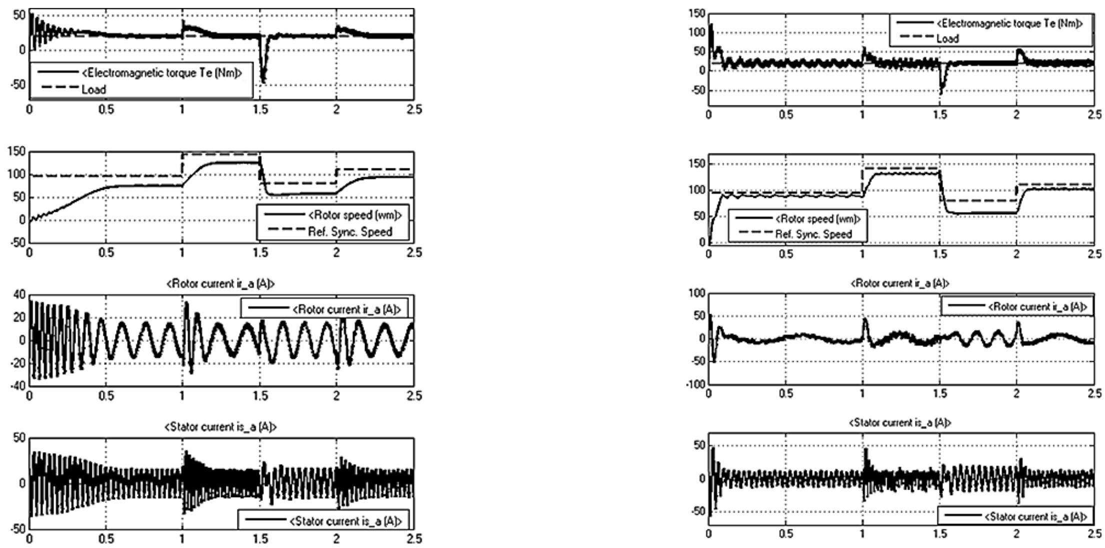
4.3 Case 3: Variable speed operation under constant load

In this case study, the IM is operated at 20 Nm constant load and variable speed command state, and the results obtained are illustrated in Figure 12. In this case study for the both models, start-up reference is applied as 100 rad/s and the reference command is increased up to 140 rad/s at the first second of the operation and decreased to 80 rad/s after that. It is seen that the slip in frequency necessity in SPWM to meet the applied load torque is higher and so operation speed is lower than SVPWM. On the other hand, an important advantage of the SVPWM model can be observed on short of settling times, and high performance of the system while running up to the variable reference. But, performance of the system at start-up under load in the SPWM model can be improved by increasing adjustable boost voltage as its value affects the output voltage effectiveness of the inverter.



(a) (b)

Figure 11: Case 2-Variable speed operation under no-load for the system driven by SPWM (a): and SVPWM (b).



(a) (b)

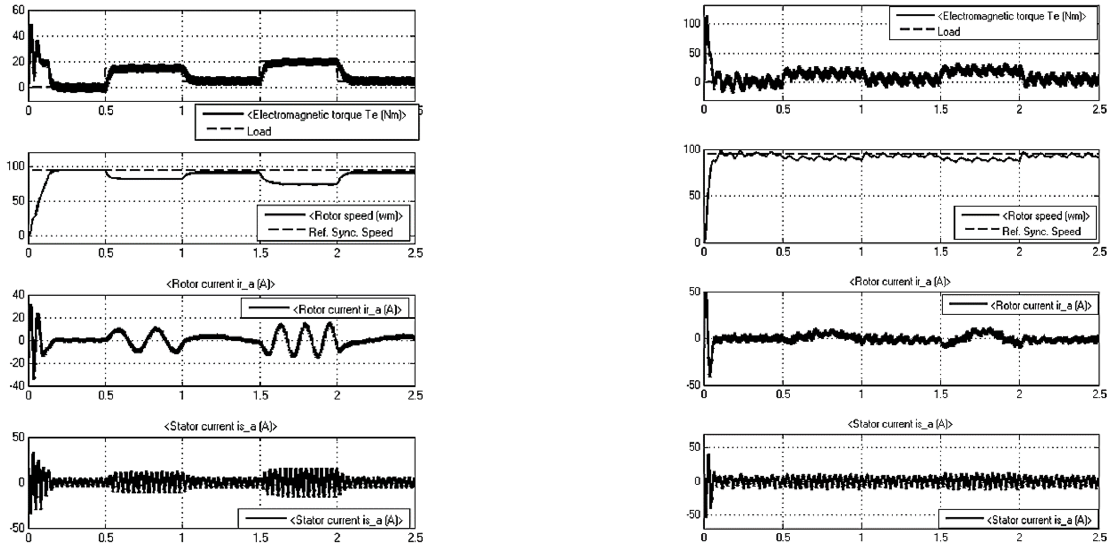
Figure 12: Case 3-Variable speed operation under constant load for the system driven by SPWM (a) and SVPWM (b).

4.4 Case 4: Constant speed operation under variable load

In this mode, the IM is driven by the both models for getting constant speed under variable load state, and obtained results are illustrated in Figure 13. The IM is operated with no-load at start up, and the load torque is updated for every 0.5 second as 10 Nm, 5 Nm, and 20 Nm, respectively. The requirement of slip frequency to produce the needed electromagnetic torque causes more drops on operating speed in SPWM model compared to SVPWM-based drive system when the load torque increases. Also, magnitudes of the stator and rotor currents increased more in SPWM-driven model. It is noticed from Figure 13 that the SVPWM model produces effective results and acts more stable when the load torque changes while keeping the speed at the reference and the system also yields better results similar to V/f-based closed-loop speed control.

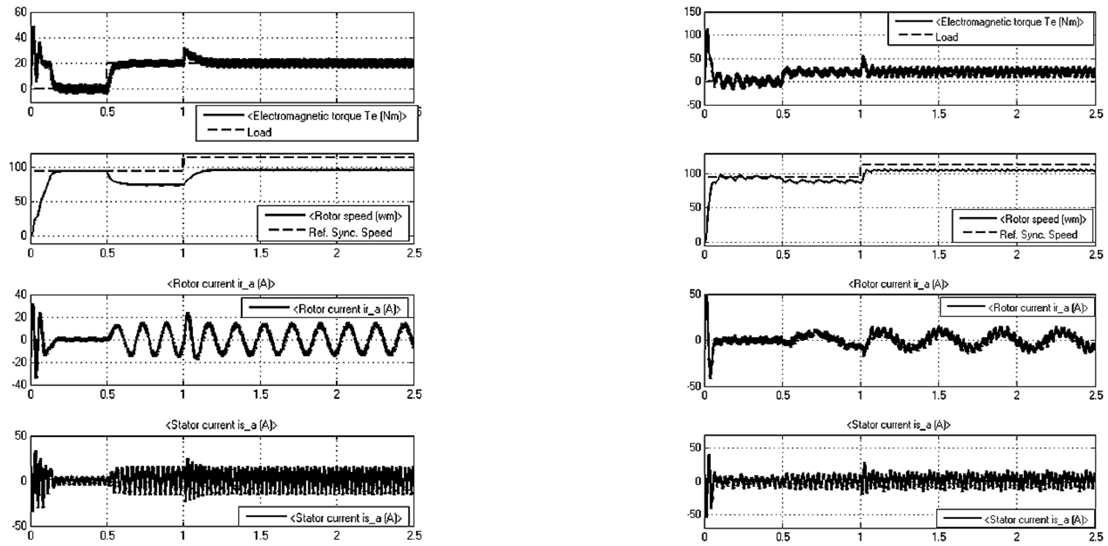
4.5 Case 5: Boost voltage application together with modified reference command

In this operation, the reference command signal is modified in order to keep the mechanical speed constant against the load torque variations. IM is loaded with 20 Nm step at 0.5 second and as the recovering the speed drops, reference commands were updated. Since the drop of the mechanical speed is more in case of driving the system by SPWM, the reference command and boost voltage value can be increased more. But, it is possible to cause saturation on air gap flux because of the change in ratio of V/f if the boost voltage value is further increased without control. In SVPWM model, the reference speed command and the reference voltage vector can be increased a bit in order to return the speed to the older position without changing boost voltage and new synchronous reference. Dynamic and steady state performances of the PWM models are clearly seen from this operation, as shown in Figure 14.



(a) (b)

Figure 13: Case 4- Constant speed operation under variable loads for the system driven by SPWM. (a): and SVPWM (b).



(a) (b)

Figure 14: Case 5: Adjustable boost voltage application with modified reference command operation for the system driven by SPWM (a): and SVPWM (b).

5 Discussion

The commentaries on the obtained results from the studied models are given and discussed in this section. Adjustable boost voltage application is also criticized from point of improving the start-up performance, step response of the control systems and the other evaluation criteria for the both PWM techniques, as given in Table 2. There is no difference between Case 1 and Case 2 from point of all evaluation criteria because of unloaded operation.

Table 2: Discussion on the proposed method and comparative study for each case.

	Evaluation Criteria			
	Good start-up performance	Short settling time	Low steady-state error	Low oscillation in steady-state
Case 1	SVPWM	SVPWM	SPWM SVPWM	SPWM
Case 2	SVPWM	SVPWM	SPWM SVPWM	SPWM
Case 3	SVPWM	SVPWM	SVPWM	SPWM SVPWM
Case 4	SVPWM	SVPWM	SVPWM	SPWM
Case 5	SPWM SVPWM	SPWM SVPWM	SPWM SVPWM	SPWM SVPWM

6 Conclusion

A comparison study on SPWM and SVPWM techniques from the point of control performance of the V/f-based scalar speed control of the IMs operating under variable speed-load conditions is introduced and the simulation results are analyzed in relevant sections. Besides, the adjustable boost voltage application along with and the modified reference speed command for increasing performance of the V/f-based speed control of IM is also proposed.

The results show that settling time to the reference in SVPWM model is shorter and maximum torque produced is higher than that of SPWM model's at all conditions although, steady-state behavior of the system is more stable in SPWM model only under no-load conditions. However, performance of the system at start-up under load in the SPWM model is improved by increasing adjustable boost voltage and updating the reference control command in scale of the current involved and the load at start-up. It was also emphasized that SVPWM technique is more effective than SPWM in terms of V/f-based speed control performance without using boost voltage application.

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