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Research Article

Simulation of Permanent Magnet Synchronous Motor Driven by a Two-Level SPWM Inverter

Oğuz Tahmaz[1*], Ali Bekir Yıldız[2]

[1] Kocaeli University, Faculty of Engineering, Electrical Engineering Department, Kocaeli, Turkey (ORCID: 0000-0001-8184-5686)
[2] Kocaeli University, Faculty of Engineering, Electrical Engineering Department, Kocaeli, Turkey (ORCID: 0000-0003-4043-7859)

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Abstract

In this study, a permanent magnet synchronous motor (PMSM) was driven by a two-level inverter modeled in MATLAB / Simulink environment. A simulation model has been created that can give results compatible with the results in real test setups. In order to obtain realistic results and waveforms, equivalent models were used instead of ideal models. For example, the use of PMSM electrical and mechanical equivalent models, adding resistance and inductance to the grid side, and modeling the DC bus capacitor with equivalent series resistance (ESR) will ensure the convergence of the obtained results to the results from real test setups. Open-loop control of PMSM has been provided. Gate signals required for semiconductor switches were produced by SPWM (Sinusoidal Pulse Width Modulation) switching method. The working principle of this PWM (Pulse Width Modulation) method has been studied in detail. In order to understand the structures on the inverter, simulation models, important parameters, and mathematical equations are given in the relevant sections respectively. In the given simulation outputs, the current-voltage waveforms of many important points on the inverter and PMSM were examined. Current drawn from the grid, voltage ripple on the DC bus capacitor, switching patterns produced by the SPWM method, inverter output phase currents, motor phase-to-neutral voltages, motor phase-to-phase voltages are the waveforms that are considered as important and presented within the scope of this study. In particular, the inverter output current-voltage signals are given for power calculation. After all these basic examinations, the inverter output power, as known as the motor input power, was measured. The phase angle between the motor phase current and phase-neutral voltage was found. Finally, these measurements made in the Simulink environment were compared with theoretical calculations and the accuracy of the models was proved.

Keywords: Motor Drive, 2-Level Inverter, Voltage Source Inverter(VSI), SPWM, PMSM, Simulation, Simulink, Modeling.

İki Seviyeli SPWM Evirici ile Tahrik Edilen Sabit Mıknatıslı Senkron Motorun Simülasyonu

Öz

Bu çalışmada, MATLAB/Simulink ortamında modellenen iki-seviyeli bir evirici ile sabit mıknatıslı senkron motor(SMSM) tahrik edilmiştir. Gerçek test düzeneklerindeki sonuçlara uyumlu sonuçlar verebilecek bir simülasyon modeli oluşturulmuştur. Gerçeğe uygun sonuçlar ve dalga şekilleri elde edebilmek için ideal modeller yerine eşdeğer modeller kullanılmıştır. Örneğin, SMSM elektriksel ve mekanik eşdeğer modellerinin kullanılması, şebeke tarafına direnç ve endüktans katkılanması ve DC bara kapasitörünün eşdeğer direnci(ESR) ile birlikte modellenmesi elde edilen sonuçların gerçek test düzeneklerinden alınan sonuçlara yakınsamasını sağlayacaktır. SMSM, açık-çevrim olarak kontrol edilmiştir. Yarı-iletken anahtarlar için gerekli kapı işaretleri SPWM(Sinüzoidal Darbe Genişlik Modülasyonu) anahtarlama yöntemi ile üretilmiştir. Bu PWM(Darbe Genişlik Modülasyonu) yönteminin çalışma mantığı detaylı olarak incelenmiştir. Evirici üzerindeki yapıların anlaşılması için simülasyon modelleri, önemli parametreler ve

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[*] Corresponding Author: Kocaeli University, Faculty of Engineering, Electrical Engineering Department, Kocaeli, Turkey, ORCID: 0000-0001-8184-5686, oguztahmaz@gmail.com

matematiksel denklemler ilgili bölümlerde sırasıyla verilmiştir. Verilen simülasyon görüntülerinde evirici ve SMSM üzerindeki birçok önemli noktanın akım-gerilim dalga şekilleri incelenmiştir. Şebekeden çekilen akım, DC bara kapasitörü üzerindeki gerilim dalgalanması, SPWM yöntemiyle üretilen anahtarlama işaretleri, evirici çıkış faz akımları, motor faz-nötr gerilimleri, motor faz-faz gerilimleri önemli görülen ve bu çalışma kapsamında sunulan işaretlerdir. Özellikle, güç hesabının yapılabilmesi için evirici çıkış akım-gerilim işaretleri verilmiştir. Tüm bu temel incelemelerden sonra, evirici çıkış gücü yani motor giriş gücü ölçülmüştür. Motor faz akımı ve faz-nötr gerilimi arasındaki faz açısı bulunmuştur. Son olarak Simulink ortamında yapılan bu ölçümler, teorik hesaplamalarla kıyaslanmış ve modellerin doğruluğu ispatlanmıştır.

Anahtar Kelimeler: Motor Sürücü, 2-Seviyeli Evirici, Gerilim Kaynağı Evirici, SPWM, SMSM, Simülasyon, Simulink, Modelleme

1. Introduction

The need for permanent magnet synchronous motors(PMSM) has increased with the development and increase of electric vehicles and industrial robot applications in recent years. These motors stand out with their power density, simple structure, small size, light weight, high power factor, precision and efficiency[1],[6].

Since variable frequency and voltage are required to drive the PMSM at different power levels and speeds, motor drives are required[2]. Thanks to power electronics technology, PMSMs and motor drives have been widely used[3].

PWM (Pulse Width Modulation) techniques can be used to drive the gates of power semiconductors in motor drives. These techniques are very important since analog systems can be controlled with microcontroller digital outputs[4].

Carrier-based Sinusoidal PWM (SPWM) and Space Vector PWM (SVPWM) are widely used for three-phase voltage source inverters[5]. The SVPWM method, which has been prominent and frequently preferred in recent years, is compared to SPWM; it has started to be preferred as a PWM method because of the utilization of DC bus, improving motor torque fluctuations, and reducing harmonics in phase currents[6]. SPWM switching technique will be used as a basis for this study.

2. Material and Method

All parameters and schematics are given in the relevant parts in detail.

2.1. Grid, Rectifier, Inverter Model

The grid voltage is rectified by a full wave rectifier and the bulk capacitor at the input is charged. Thus, DC bus voltage is generated. The model of the grid side is given in figure 1 and the important parameters of grid side are given in table 1.

Table 1. Important parameters of grid and bulk capacitor

Parameters	Description	Value
V_{grid}	*Grid Voltage*	*220 V_{ac}*
R_{grid}	*Grid Resistance*	*25 mΩ*
L_{grid}	*Grid Inductance*	*10 µH*
C_{dc_link}	*Capacity of Bulk Capacitor*	*1230 µF*
R_{dc_link}	*Equivalent Series Resistance(ESR) of Capacitor*	*50 mΩ*

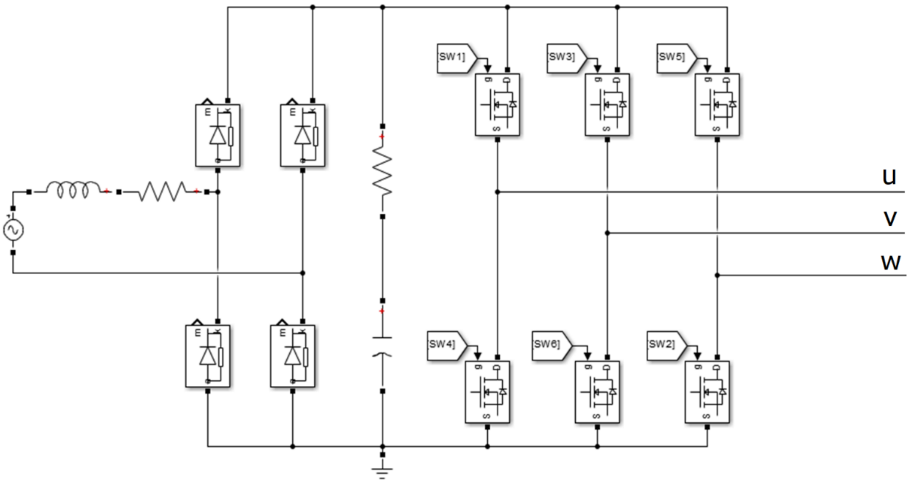

Figure 1. Grid, Rectifier, Inverter model in MATLAB/Simulink

2.2. PMSM Electrical Model

The electrical equivalent circuit of three-phase PMSM was modeled with resistance, inductance and back EMF (electromotive force). The electrical model of the motor is given in figure 2.

Rotor's electrical position as known θ_e and mechanical speed as known ω_m were measured and PMSM's required electrical model parameters are given in table 2 in order to calculate the back EMF voltages(e_u, e_v, e_w) in the motor electrical equivalent circuit instantaneously. Calculations were made according to equation 1.

Since the motor is assumed to be rotating in steady-state condition and at a constant speed, the back EMF source in the electrical equivalent circuit of the motor produces a sinusoidal wave with constant amplitude. There are phase differences of 120 degrees between the back EMF voltages of motor phases.

$$\begin{bmatrix} e_u(t) \\ e_v(t) \\ e_w(t) \end{bmatrix} = K_e \omega_m(t) \begin{bmatrix} cos\left(\theta_e(t)\right) \\ cos\left(\theta_e(t) - \frac{2}{3}\pi\right) \\ cos\left(\theta_e(t) + \frac{2}{3}\pi\right) \end{bmatrix} \tag{1}$$

Table 2. PMSM electrical model parameters

Parameters	**Description**	**Value**
R_L	*Winding Resistance(ph-to-n)*	*580 mΩ*
L_L	*Winding Inductance(ph-to-n)*	*3.75 mH*
K_e	*Back EMF Constant*	*24.4 V/krpm*

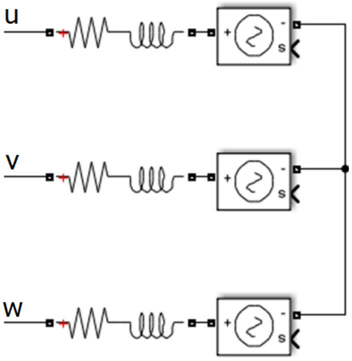

Figure 2. PMSM motor electrical model in MATLAB/Simulink

2.3. PMSM Mechanical Model

Mechanical dynamics of PMSM consist of load torque, induced torque, inertia, viscous friction, pole pair which is given in equation 2, 3. PMSM's required mechanical model parameters is given in table 3. The mechanical part of motor modeled with Simulink blocks in figure 3. PMSM test parameters are given in table 4.

$$T_e(t) = J_m \frac{d}{dt} \omega_m(t) + B_m \omega_m(t) + T_L(t) \tag{2}$$

$$\frac{d}{dt} \omega_m(t) = \frac{T_e(t) - T_L(t) - B_m \omega_m(t)}{J_m} \tag{3}$$

Table 3. PMSM mechanical model parameters

Parameters	**Description**	**Value**
J	*Inertia*	*0.269*10^{-6} kg.m2*
B	*Viscous Friction*	*5.410*10-3 Nm.s*
P	*Pole Pair*	*5*

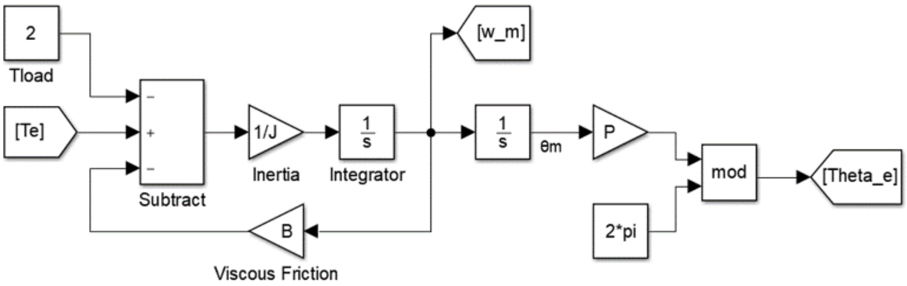

Figure 3. PMSM mechanical model in MATLAB/Simulink

Table 4. PMSM test conditions

Parameters	Description	Value
T_L	*Load Torque*	*2 Nm*
ω_m	*Nominal Motor Speed*	*3000 min^{-1}*

Equations 4 and 5 are used to calculate the torque as known as T_e obtained from the energy conversion occurring in the air gap of the motor. This equation modeled with Simulink blocks in figure 4.

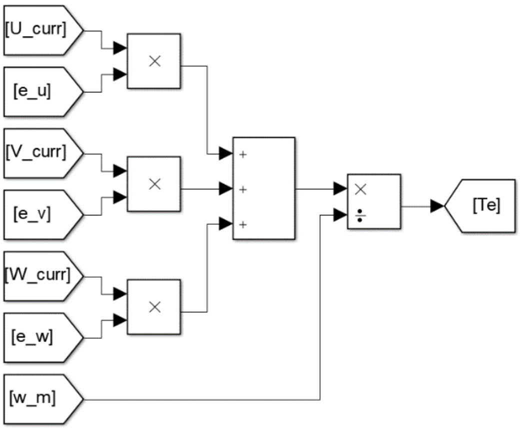

Figure 4. Calculation of induced torque in MATLAB/Simulink

$$T_e(t) = \frac{p(t)}{\omega_m(t)} \tag{4}$$

$$T_e(t) = \frac{e_u(t)i_u(t) + e_v(t)i_v(t) + e_w(t)i_w(t)}{\omega_m} \tag{5}$$

2.4. SPWM Technique

SPWM (Sinusoidal PWM) is one of the carrier-based PWM types in which two signals are compared. These signals are called carrier and modulation signals. The carrier signal is in the triangle waveform. The frequency of the carrier signal is also referred to as the switching frequency in the literature.

The modulation signal can be in any waveform. In this method, the modulation signal is in the form of a sinusoidal wave. Switching elements are triggered with obtained PWM signals.

The modulation index which given in is the ratio of the peak value of the reference signal to the peak value of the carrier signal. The maximum modulation index value can be 1. Calculation of modulation index is given in equation 6.

$$m_a = \frac{\widehat{V_m}}{\widehat{V_c}} \tag{6}$$

Motor phase-to-neutral peak and effective voltages(fundamental component) are calculated respectively by the equation 7 and 8.

$$\widehat{V_{ph\_to\_n}} = m_a \frac{\widehat{V_{DC}}}{2} \quad (7)$$

$$V_{ph\_to\_n\_rms} = \frac{1}{2\sqrt{2}} m_a V_{DC} \quad (8)$$

Motor phase-to-phase effective voltages (fundamental component) are calculated by the equation 9.

$$V_{ph\_to\_ph\_rms} = \frac{\sqrt{3}}{2\sqrt{2}} m_a V_{DC} \quad (9)$$

Sinusoidal waveforms at constant amplitude and frequency are modulation signals that determine the fundamental frequency of motor currents. Sinusoidal modulation waveforms are given in figure 5.

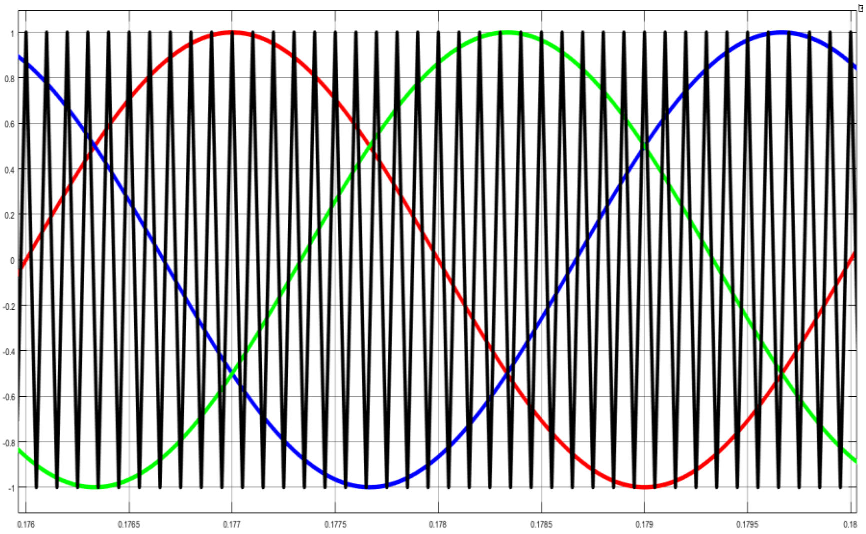

Figure 5. Modulation and carrier waveforms

Required PWM signals to switch the high-side semiconductor devices in the half-bridge structure shown in figure 1 is generated with the SPWM technique and the signals are obtained as a result of sine-triangle comparisons shown in figure 6.

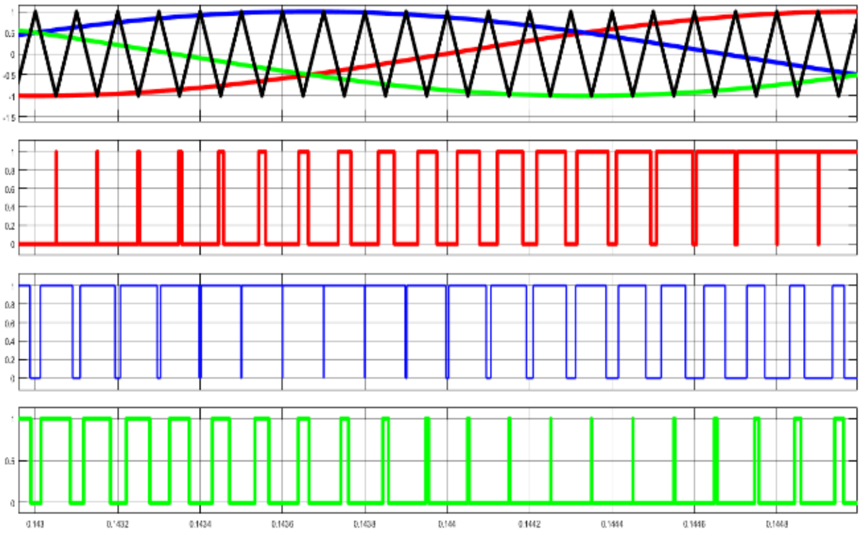

Figure 6. Generation of PWM Signals with SPWM

The inversion example of the high-side signals in figure 6 is taken in figure 7 to generate switching signals for the low-side switches in half-bridge structure. The possibility that high and low side switches are in conduction at the same time will cause a shoot through problem in the inverter. Mostly, dead-time is added between these signals.

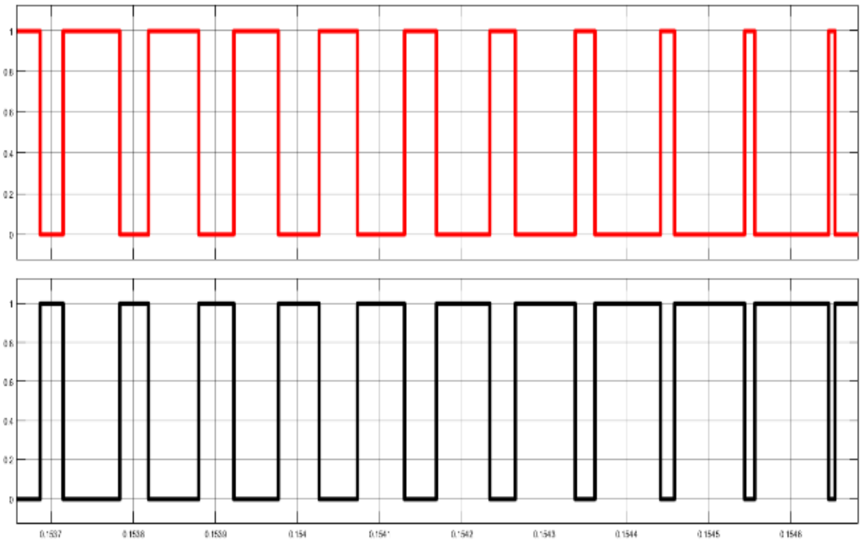

Figure 7. Switching signals for high and low side switches

3. Results and Discussion

3.1. General Simulation Model and Simulation Outputs

The detailed MATLAB/Simulink model to clarify this study in detail is shown in figure 13. The important waveforms and outputs of the simulation are given in this part.

The nominal speed was given as the starting condition in the simulation in order to overcome the problem of synchronization to the stator field while operating synchronous motors.

Load torque and speed variables were defined parametrically. The motor speed can be changed by the frequency of reference signal.

In summary, open-loop controlled, synchronous, 3 phase motor drive which fed from grid, the simulation was made with PMSM's nominal load torque of 2 Nm and nominal speed of 3000 min^{-1}.

Grid voltage(orange), grid current(magenta) and, DC bus voltage(green) are given in the simulation output figure 8.

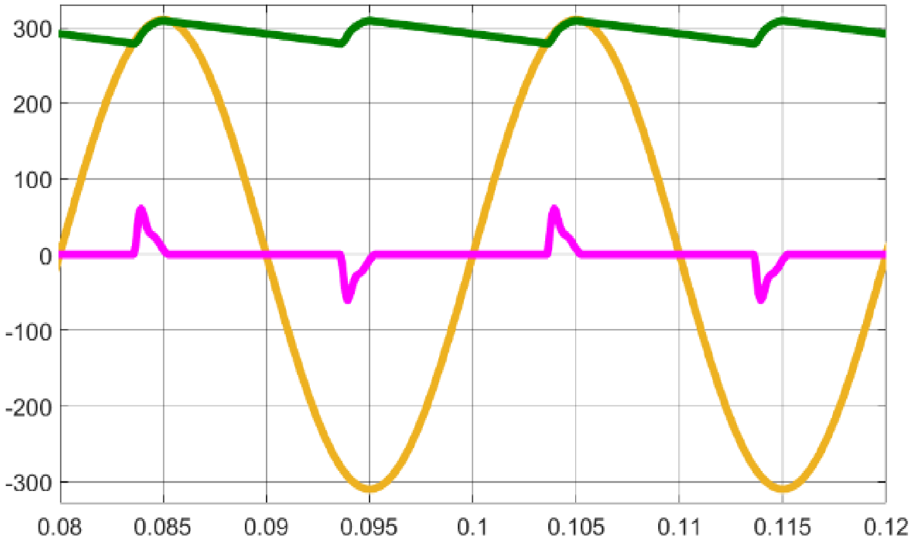

Figure 8. Grid and DC link waveforms

Instantaneous motor phase currents are given in the simulation output figure 9.

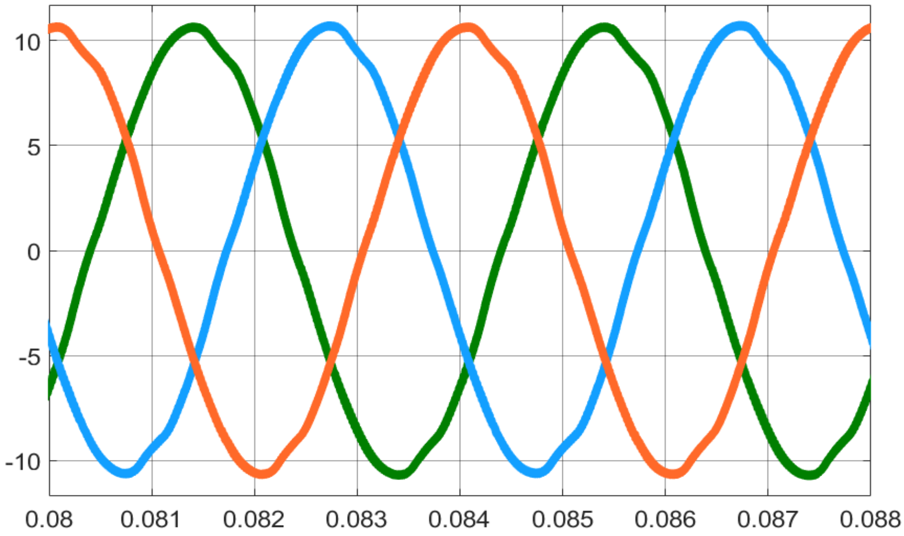

Figure 9. Motor phase currents (i_u, i_v, i_w)

Motor phase-to-neutral voltages are given in the simulation output figure 10. These values were used to calculate output power.

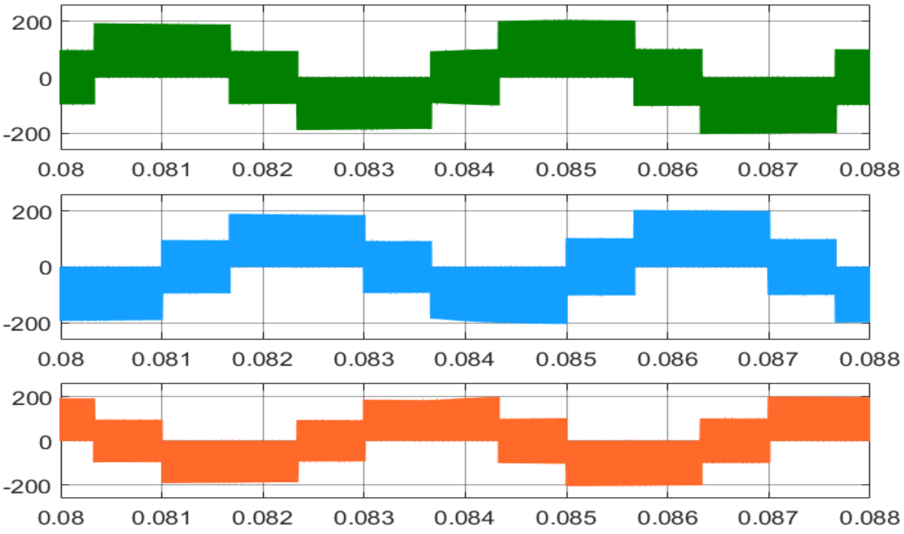

Figure 10. Motor phase-to-neutral voltages (v_{un}, v_{vn}, v_{wn})

Motor phase-to-phase voltages are given in the simulation output figure 11.

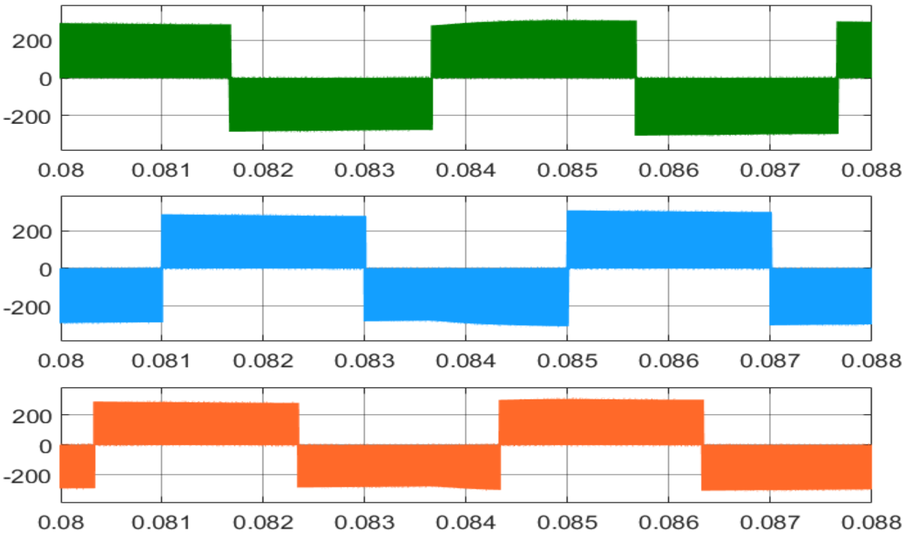

Figure 11. Motor phase-to-phase voltages (v_{uv}, v_{uw}, v_{vw})

The voltage and current of each motor phase were measured separately. The power transferred from the inverter to the motor can be obtained if the phase-neutral voltage and phase currents of the motor are known. Measured average power affecting to the motor is 1235 W. The theoretical calculations were given in equation 10,11, and 12 and the measurements were verified.

$$P_{avg} = 3\, V_{un}\, I_u \cos\varphi \tag{10}$$

$$P_{avg} = 3 * 67\ V * 7.6\ A * \cos(36^{\circ}) \tag{11}$$

$$P_{avg} = 1235\ \mathrm{W} \tag{12}$$

Phasor diagram representation of PMSM motor is given in figure 12. Phase-to-neutral voltage(V_{un}) is $67\angle 0^{\circ}$ V and phase current(I_u) is $7.6\angle\text{-}36^{\circ}$ A. Phase difference between the motor phase current and phase-to-neutral voltage is 36 degree.

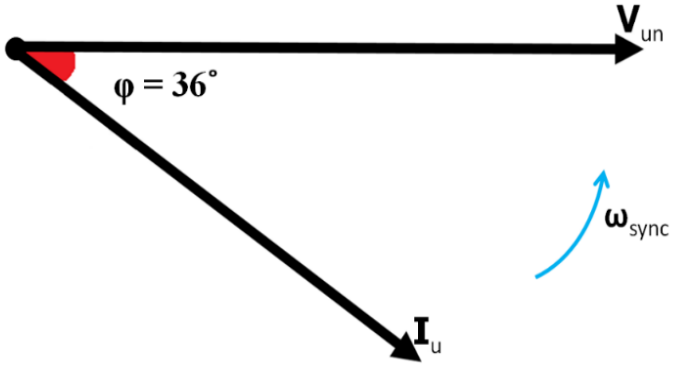

Figure 12. PMSM phasor diagram (V_{un}, I_u)

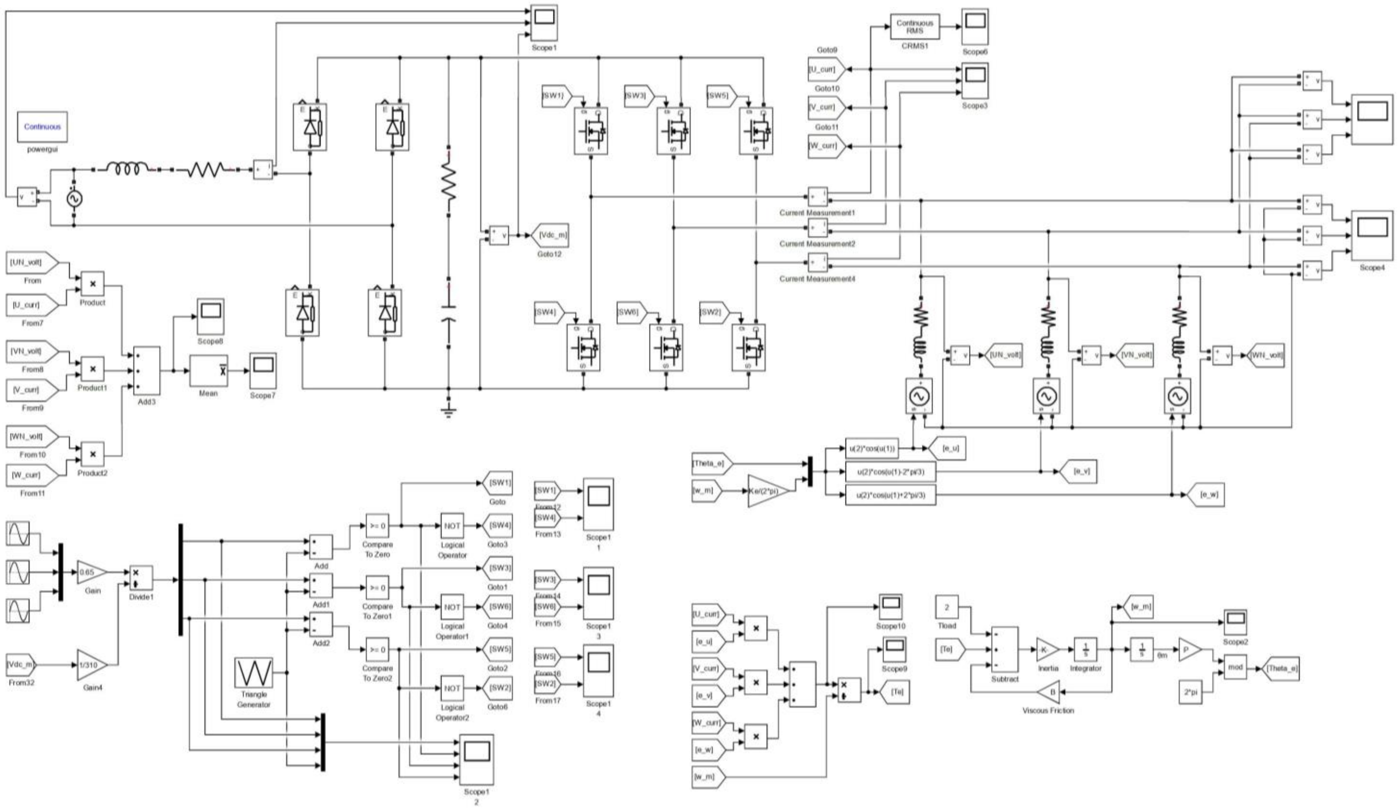

Figure 13. System model in MATLAB/Simulink environment

3.2. Discussion

All models which were created with experimental parameters in this study were designed to obtain approximate test outputs without actual test setups. Waveforms observed in simulation scopes are very close to principal waveforms and plausible. In this study, the most basic equivalent circuits were modeled, but in order to make the simulation outputs more convergent to the actual test results, the stray inductances and stray resistances caused by the copper tracks on the inverter electronic PCB(printed circuit board), component leads can also be added parametrically to the simulation. In fact, the effects of the connectors and motor cable, their parasitic inductance, parasitic capacitance and resistance can also contribute to the simulation.

4. Conclusions and Recommendations

The 2-level inverter fed from the grid, permanent magnet synchronous motor were modeled in MATLAB/Simulink environment, and required switching signals of the inverter were generated with the SPWM technique. In addition, all current and voltage patterns on the inverter and motor were examined. Finally, the output power of the inverter was obtained. The simulation which presented in this study, is very suitable for studying and making predictions on a 2-level SPWM inverter before preparation of the test setup and then be compared with the actual measurements.

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