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Şebeke-bağlantılı Solar NNK İnverterde Güç ve Harmonik Kayıplarının İyileştirilmesi için Etkin Modülasyon Yöntemlerinin Gerçekleştirilmesi

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Öz

Enerji talebindeki artış, fosil yakıt fiyatlarının yükselmesi ve sera gazı emisyonlarının yüksek seviyelere ulaşması, temiz ve yenilenebilir enerji kaynaklarının büyük ölçekli entegrasyonuna gerek duyulmasını sağlamıştır. Solar fotovoltaik (FV) sistemler, geleneksel şebekelerde ortaya çıkan zorlukların aşılması için kullanılabilecek potansiyel enerji kaynaklarındandır. Güç ve harmonik içeriğinin optimize edilmesi için etkili güç dönüşüm topolojilerinin kullanımı, FV sistemlerin önemli hale gelen ihtiyaçlarındandır. Üç seviyeli Nötr Nokta Kenetlemeli (NNK) inverter, geleneksel ve iki seviyeli inverterlerle karşılaştırıldığında daha az harmonik üretir ve güç miktarını artırır. Bu amaçla bu çalışmada, şebekeye bağlı 250 kW solar FV sistem için anahtarlama işlemini ve güç kayıplarını optimize etmek amacıyla üç seviyeli NNK inverter uygulaması sunulmuştur. Ayrıca, güç üretimi, akım ve gerilim karakteristikleri, ve hızlı Fourier dönüşümü analizi MATLAB / Simulink ortamında Simpowersystem ve Simelectronics alt programları yardımıyla gerçekleştirilmiştir. Önerilen NNK inverterde, anahtarlama ve güç kayıplarını optimize etmek için sinüzoidal PWM ve uzay vektör PWM yöntemleri, IGBT güç anahtarlarının iletim süresini kontrol etmek amacıyla kullanılmıştır. Önerilen inverterin şebeke tarafındaki 3 fazlı AC çıkış gerilimi, 3 fazlı gerilim yükseltici transformatör vasıtasıyla 15 kV gerilim seviyesinde şebekeye bağlanmıştır. 3 fazlı şebekeye bağlı sistem için önerilen çalışmanın performans değerlendirmesi kısmında uzay vektör PWM yönteminin sinüzoidal PWM yöntemine göre etkinliği gösterilmiştir.

Anahtar Kelimeler: NNK inverter, sinüzoidal PWM, uzay vektör PWM, solar FV dizi, toplam harmonik bozulma

The Implementation of Effective Modulation Schemes to Improve the Power and Harmonic Losses in Grid-Tied Solar NPC Inverter

Abstract

The growing energy demand, rising fossil fuel prices, and exceeding greenhouse gas emissions require large-scale integration of clean and renewable energy resources. Solar Photovoltaic (PV) system is the potential prospective energy resource to overcome the challenges of conventional grid. Effective power conversion topologies are the prominent need of the PV system to optimize the power and harmonic contents. Three level neutral point clamped (NPC) inverter comparatively produces less harmonics and increases the power delivery compared to the conventional and two-level inverters. Therefore, this research presents the deployment of three level NPC inverter to optimize the switching and power losses in grid connected 250 kW solar PV array. Moreover, power generation, current and voltage characteristics, and fast Fourier transform analysis is performed in MATLAB / Simulink directory with the help of Simpowersystem and Simelectronics toolboxes. To optimize the switching and power losses, sinusoidal PWM and space vector PWM are used to control the duty cycle of IGBT power switches in the proposed NPC inverter. The grid side 3 phase AC output voltage of the proposed inverter is connected to 15 kV grid with the help of 3 phase step up transformer. For 3 phase grid-tied system, the performance evaluation section of the proposed research shows the effectiveness of space vector PWM over sinusoidal PWM.

Keywords: NPC inverter, sinusoidal PWM, space vector PWM, Solar PV array, total harmonic distortion

1. Introduction

Growth in global power consumption, rising fossil fuel prices, and exceeding toxic emissions needs large-scale integration of clean and viable renewable energy resources. Solar Photovoltaic (PV) is an abundant and clean energy resource hence, significant increase in solar PV installation is observed from 2006 to 2016 for balancing the massive energy demand as depicted Figure 1 [1]. Depending on the geographical location and potentiality, solar PV is categorized into stand-alone and grid-connected topology [2]. In stand-alone topology, PV directly offers small scale applications including; house heating, water pumping etc. Grid-connected technology establishes bi-directional power flow between the consumer and the grid [3]. Despite various benefits of solar PV technology, the intermittency, low power efficiency of solar panel and major switching losses in power converters limits its practical applications. Therefore, the efficient power conversion technologies are the prominent need of the solar PV system to minimize the switching losses in power electronics components of solar PV converters.

Pulse Width Modulation (PWM) is used as major controlling element in power inverters which plays significant role to optimize the switching losses and enhance the efficiency of the solar PV generation. The authors in [4] and [5] declared that the implementation of appropriate modulation schemes reduces the switching losses and THD which further help to increase the net efficiency of the PV system. The high switching frequency based THD reduction solution is proposed by the authors in [6] while, higher frequencies also cause huge switching losses as well. Therefore, the optimization of these switching losses of converters is investigated in [7]. In addition, various PWM schemes to accomplish less harmonic in output voltage and current of the power converters are reviewed in [8] and [9]. Space Vector Modulation (SVM) yields less harmonics and offer better DC bus voltage utilization. Hence, it is one of the most widespread PWM techniques that is used in various applications of electrical power systems. SVM based efficient solution to optimize the harmonics in three phase electric drives has been proposed by the authors in [10]. Similarly, the authors in [11] accomplished SVM based fast computational experimental results of two-level voltage source inverter using Simulink and PIC microcontroller.

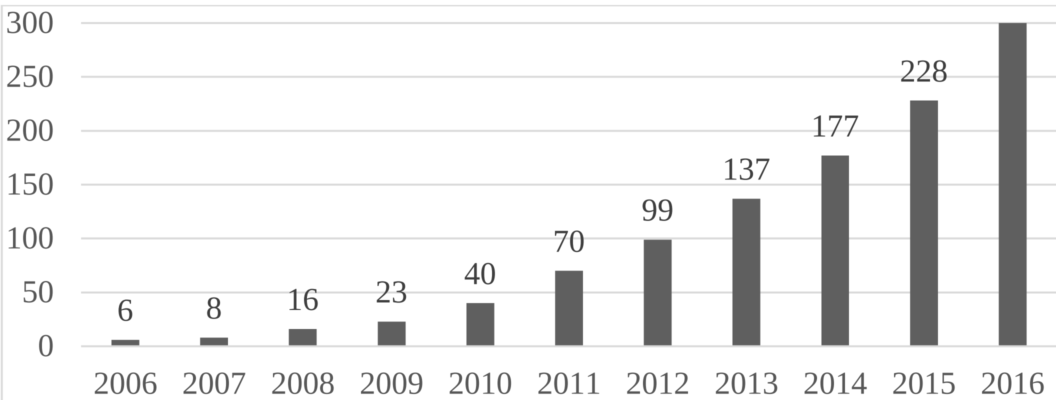

Figure 1. Solar PV installation in MW from 2006-2016

This paper performs comparative analysis of Sinusoidal and SVM PWM on a novel IC-MPPT integrated three level NPC inverter. The simulation is performed in MATLAB/Simulink by using Simpowersystem and Simelectronics Toolboxes at NPC inverter of 250 kW solar PV array. Fast Fourier transform (FFT) analysis clarifies the effectiveness of SVM over sinusoidal PWM. The simulation results of net power generation of solar PV, PV characteristics, comparative analysis of sinusoidal and SVM PWM, and harmonic analysis are demonstrated in performance evaluation section. The rest of the paper is organized as follows: Section 2 illustrates the introduction, operation, switching states, and effectiveness of NPC multi-level inverter. The detailed description of sinusoidal and SVM is performed in Section 3. Performance evaluation of the proposed model is described in Section 4. Section 5 concludes the paper with the summary of the simulation results of the proposed work.

2. Neutral Point Clamped Inverter

The advent of MLIs topology offers great benefits to the grid-tied solar PV system by reducing the voltage steps (dV/dt) in the output voltage of the inverter. This voltage step reduction minimizes the power losses and reduces the stress on bearing and isolations of renewable power conversion systems [12]. Recently, widely used MLIs are: cascaded bridge converter, flying capacitor converter, and diode-clamped or neutral point clamped (NPC) inverter. This research focuses on the NPC inverter topology in the presence of sinusoidal and SVPWM technique.

NPC inverter is widely used for many electrical applications due to low leakage current, less harmonics, and high efficiency [13]. In NPC inverter, the DC source voltage is equally distributed using two series capacitors at DC side of the three-phase inverter. Three voltage levels are achieved using two capacitors and their central connecting point: $+0.5V_{DC}$, 0, and $-0.5V_{DC}$. NPC is composed of total 12 switches named; S_{a1} S_{a2} S_{a3} S_{a4} S_{b1} S_{b2} S_{b3} S_{b4} S_{c1} S_{c2} S_{c3} S_{c4} and six diodes as demonstrated in Figure 2. The upper and lower switches of each leg are complementary in nature.

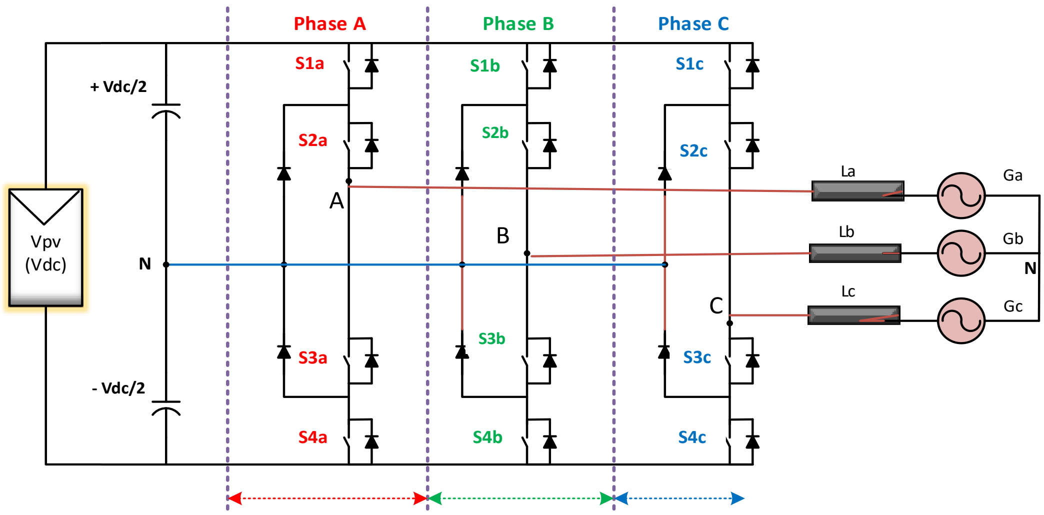

Figure 2. Schematic Diagram of Grid Tied PV NPC Inverter

The clamping diodes are used by central switches to achieve the neutral point or zero dc-link point so called neutral point inverter. The appropriate switching pattern in NPC inverter gives rise to the desired three phase AC output voltage. The upper six switches need to be controlled, while the lower six switches are complementary of the upper ones. The upper and lower clamping diodes in each leg support to attain the neutral point. The main difference between existing six step inverters, 2 level inverters, and the proposed NPC inverter is the addition of these clamping diodes to achieve third levels in pole voltages that in turns reduce the harmonics in output voltage.

When both upper switches S_{a1}, S_{a2} are switched ON, then complementary switches S_{a3}, S_{a4} will be OFF. Therefore, the current will flow from the upper capacitor C1 through S_{a1} and S_{a2} towards zero dc-link, the voltage +0.5

V_{DC} will appear across the load. Conversely, if S_{a1} and S_{a2} are switched OFF, then S_{a3} and S_{a4} will be ON. Hence, lower switches cause -0.5 V_{DC} to appear across the load. Similar way, the zero voltage will appear with the help of clamping diodes when central switches S_{a2} and S_{a3} turned ON and respective diode conduct. Three voltage levels (+0.5 V_{DC}, 0, -0.5 V_{DC}) appear at each pole hence, it is known as three level NPC inverter. Due to three voltage levels, totally (3×3×3 = 27) possible switching states exist for all three phases of the inverter. Switching states and voltage levels are listed in Table 1.

Table 1. Vector states of NPC inverter based on space vector modulation

Voltage Vectors	Switching Seq.			Pole Voltages			Line Voltages			Phase Voltages		
	a	b	c	V_{A0}	V_{B0}	V_{C0}	V_{AB}	V_{BC}	V_{CA}	V_{AN}	V_{BN}	V_{CN}
V_0	0	0	0	0	0	0	0	0	0	0	0	0
V_0	N	N	N	$-V_{DC}/2$	$-V_{DC}/2$	$-V_{DC}/2$						
V_0	P	P	P	$V_{DC}/2$	$V_{DC}/2$	$V_{DC}/2$						
V_1	P	0	0	$V_{DC}/2$	0	0	$V_{DC}/2$	0	$-V_{DC}/2$	$V_{DC}/3$	$-V_{DC}/6$	$-V_{DC}/6$
V_1	0	N	N	0	$-V_{DC}/2$	$-V_{DC}/2$						
V_2	P	P	0	$V_{DC}/2$	$V_{DC}/2$	0	0	$V_{DC}/2$	$-V_{DC}/2$	$V_{DC}/6$	$V_{DC}/6$	$-V_{DC}/3$
V_2	0	0	N	0	0	$-V_{DC}/2$						
V_3	0	P	0	0	$V_{DC}/2$	0	$-V_{DC}/2$	$V_{DC}/2$	0	$-V_{DC}/6$	$V_{DC}/3$	$-V_{DC}/6$
V_3	N	0	N	$-V_{DC}/2$	0	$-V_{DC}/2$						
V_4	0	P	P	0	$V_{DC}/2$	$V_{DC}/2$	$-V_{DC}/2$	0	$V_{DC}/2$	$-V_{DC}/3$	$V_{DC}/6$	$V_{DC}/6$
V_4	N	0	0	$-V_{DC}/2$	0	0						
V_5	0	0	P	0	0	$V_{DC}/2$	0	$-V_{DC}/2$	$V_{DC}/2$	$-V_{DC}/6$	$-V_{DC}/6$	$V_{DC}/3$
V_5	N	N	0	$-V_{DC}/2$	$-V_{DC}/2$	0						
V_6	P	0	P	$V_{DC}/2$	0	$V_{DC}/2$	$V_{DC}/2$	$-V_{DC}/2$	0	$V_{DC}/6$	$-V_{DC}/3$	$V_{DC}/6$
V_6	0	N	0	0	$-V_{DC}/2$	0						
V_7	P	0	N	$V_{DC}/2$	0	$-V_{DC}/2$	$V_{DC}/2$	$V_{DC}/2$	$-V_{DC}$	$V_{DC}/2$	0	$-V_{DC}/2$
V_8	0	P	N	0	$V_{DC}/2$	$-V_{DC}/2$	$-V_{DC}/2$	V_{DC}	$-V_{DC}/2$	0	$V_{DC}/2$	$-V_{DC}/2$
V_9	N	P	0	$-V_{DC}/2$	$V_{DC}/2$	0	$-V_{DC}$	$V_{DC}/2$	$V_{DC}/2$	$-V_{DC}/2$	$V_{DC}/2$	0
V_{10}	N	0	P	$-V_{DC}/2$	0	$V_{DC}/2$	$-V_{DC}/2$	$-V_{DC}/2$	V_{DC}	$-V_{DC}/2$	0	$V_{DC}/2$
V_{11}	0	N	P	0	$-V_{DC}/2$	$V_{DC}/2$	$V_{DC}/2$	$-V_{DC}$	$V_{DC}/2$	0	$-V_{DC}/2$	$V_{DC}/2$
V_{12}	P	N	0	$V_{DC}/2$	$-V_{DC}/2$	0	V_{DC}	$-V_{DC}/2$	$-V_{DC}/2$	$V_{DC}/2$	$-V_{DC}/2$	0
V_{13}	P	N	N	$V_{DC}/2$	$-V_{DC}/2$	$-V_{DC}/2$	V_{DC}	0	$-V_{DC}/2$	$2V_{DC}/3$	$-V_{DC}/3$	$-V_{DC}/3$
V_{14}	P	P	N	$V_{DC}/2$	$V_{DC}/2$	$-V_{DC}/2$	0	V_{DC}	$-V_{DC}$	$V_{DC}/3$	$V_{DC}/3$	$-2V_{DC}/3$
V_{15}	N	P	N	$-V_{DC}/2$	$V_{DC}/2$	$-V_{DC}/2$	$-V_{DC}$	V_{DC}	0	$-V_{DC}/3$	$2V_{DC}/3$	$-V_{DC}/3$
V_{16}	N	P	P	$-V_{DC}/2$	$V_{DC}/2$	$V_{DC}/2$	$-V_{DC}$	0	V_{DC}	$-2V_{DC}/3$	$V_{DC}/3$	$V_{DC}/3$
V_{17}	N	N	P	$-V_{DC}/2$	$-V_{DC}/2$	$V_{DC}/2$	0	$-V_{DC}$	V_{DC}	$-V_{DC}/3$	$-V_{DC}/3$	$2V_{DC}/3$
V_{18}	P	N	P	$V_{DC}/2$	$-V_{DC}/2$	$V_{DC}/2$	V_{DC}	$-V_{DC}$	0	$V_{DC}/3$	$-2V_{DC}/3$	$V_{DC}/3$

3. Modulation Strategies for NPC Inverter

PWM strategies are the main power control circuitry use in solar PV and wind energy conversion systems. The period, frequency and duty cycle are important characteristics of PWM which are defined in (1), (2) and (3) respectively.

$$Time\ Period = T_{ON} + T_{OFF} \tag{1}$$

$$Frequency = 1/Time\ Period \tag{2}$$

$$Duty\ Cycle = \frac{T_{ON}}{T_{ON} + T_{OFF}} \times 100 \tag{3}$$

Sinusoidal PWM consists of low frequency sinusoidal reference signal and high frequency triangular carrier signal. Total number of pulses in one half cycle define the frequency of the carrier signal. The output voltage of the inverter depends on the value of modulation index M and the peak amplitude of the reference signal. Equations (4) and (5) define the modulation index and modulation frequency respectively. The rms output voltage is modelled in (6).

$$M = A_r/A_c \tag{4}$$

$$m_f = f_c/f_r \tag{5}$$

$$V_o = V_s\left(\sum_{m=1}^{p}\frac{D_m}{\pi}\right)^{1/2} \tag{6}$$

3.1. Space Vector Pulse Width Modulation

This research further proceeds with the detailed description of space vector modulation and Fourier analysis is performed for both techniques to compute the harmonic contents.

The reference voltage is the desired output which can be given to the system. SVPWM is the approximation of rotating reference voltage space vector. The utilization of SVPWM require few important steps. According to [14] the transformation of (a, b, c) to (α, β) frame is the crucial task. Three-phase voltages can be transformed in two phase voltages as presented in (7) and (8). The reference space vector modelled as shown in (9).

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & Cos\left({}^{2\pi}/_{3}\right) & Cos\left({}^{4\pi}/_{3}\right) \\ 0 & Sin\left({}^{2\pi}/_{3}\right) & Sin\left({}^{4\pi}/_{3}\right) \end{bmatrix}\begin{bmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & {}^{-1}/_{2} & {}^{-1}/_{2} \\ 0 & {}^{\sqrt{3}}/_{2} & {}^{-\sqrt{3}}/_{2} \end{bmatrix}\begin{bmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{bmatrix} \tag{8}$$

$$\vec{V} = \bar{V}\, e^{j\theta} \tag{9}$$

The magnitude and phase of the reference vector are presented in (10) and (11) respectively.

$$\overline{|V|} = \sqrt{{V_\alpha}^2 + {V_\beta}^2} \tag{10}$$

$$\theta = tan^{-1}\left(\frac{V_\beta}{V_\alpha}\right) \tag{11}$$

In the proposed NPC inverter, total three level for three phase system corresponds to (3×3×3=27) switching states. In NPC inverter states, ‘P’ corresponds to positive, ‘N’ shows negative, and ‘0’ represent neutral point level. By using (7) and (8), all the zero, small, medium, and large vector are calculated, and respective pole, phase and line voltage are listed in Table. 3. The desired reference voltage vector is created using the nearest three vectors that reduce harmonic contents in output of the inverter. All vector states of NPC inverter based on space vector modulation are demonstrated in Figure 3. By using voltage balancing principle as shown in (12), the space vector PWM for NPC can be performed by multiplying reference vectors with their time intervals within each sampling period.

$$\overline{V_{ref}} \times T_s = \sum \bar{V}_i \times T_i \tag{12}$$

Where, $\bar{V}_i$ and T_i are the space vector and its dwell time to compute the desired reference voltage. To calculate the dwell time, the space vector diagram is divided into major six vector. In this research, the reference vector of the highlighted area is computed. The rest of the vectors are also calculated in a similar pattern. In the highlighted area, the space vectors used to compute reference vector are; 0NN/P00 (V_1), P0N (V_7), and 00N/PP0 (V_2). While, their dwell times are T_a, T_b, and T_c respectively as modelled in (13).

$$V_{ref} \times\ T_s = (V_1 * T_a) \times (V_2 * T_c) \times (V_7 * T_c) \tag{13}$$

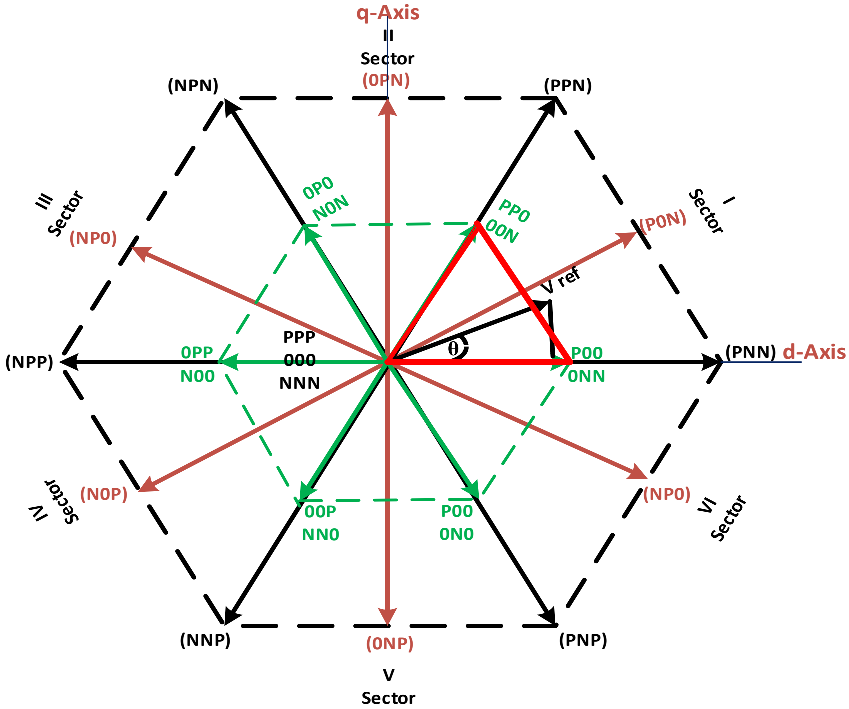

Figure 1. Space Vector Diagram of Three Level NPC Inverter

Substituting the values of space vector and mathematical calculations give rise to (14).

$$\begin{Bmatrix} T_a = T_s \times \left(1 - 2\sqrt{3}\, V_{ref} \,/\, V_d\, Sin\theta\right) \\ T_b = T_s \times \left(2\sqrt{3}\, V_{ref} \,/\, V_d\, Sin(\pi/3 + \theta) - 1\right) \\ T_c = T_s \times \left(1 - 2\sqrt{3}\, V_{ref} \,/\, V_d\, Sin(\pi/3 - \theta)\right) \end{Bmatrix} \quad (14)$$

The proper selection of state space vector and their dwell time draw the switching pattern to control the IGBT switches of NPC inverter.

4. Performance Evaluation

In the proposed research, 250 kW solar PV array is considered for the simulation analysis. MATLAB / Simulink directory is used to perform all the simulations related to power source generation, power inversion, harmonic analysis, and modulation analysis. The PV and IV characteristics of the proposed solar PV array are presented in Figure 4.

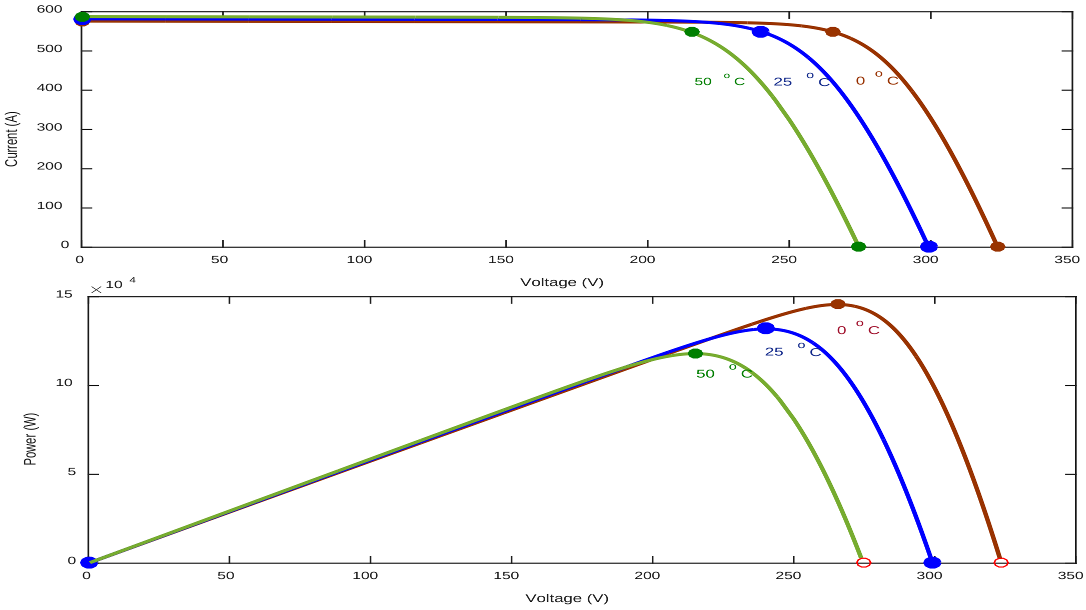

Figure 2. PV and IV characteristics of proposed PV array

The proposed grid-tied solar PV array is simulated for the fluctuating Irradiance that is varying in the range of 600 to 1000 W/m^2. Irradiance, generated voltage, current, and power generation from PV array is depicted in Figure 5. The PV array produces maximum 500 V DC and around 500 A current as well. In addition, it is cleared that current is much affected with change in irradiance.

Total 250 kW power is extracted from aforesaid PV array. The voltage from the PV array is directly sent to input of the NPC inverter. The capacitors at the input of the NPC inverter act as power generation source for the inverter. DC link capacitors also help to provide smooth voltage at input of the inverter. NPC inverter receives 500 V DC from the PV panels and control the switching of the IGBTs using PWM schemes to generate the 500 V AC. Comparative analysis of SPWM and SVPWM based on harmonic contents is performed in Figure 6.

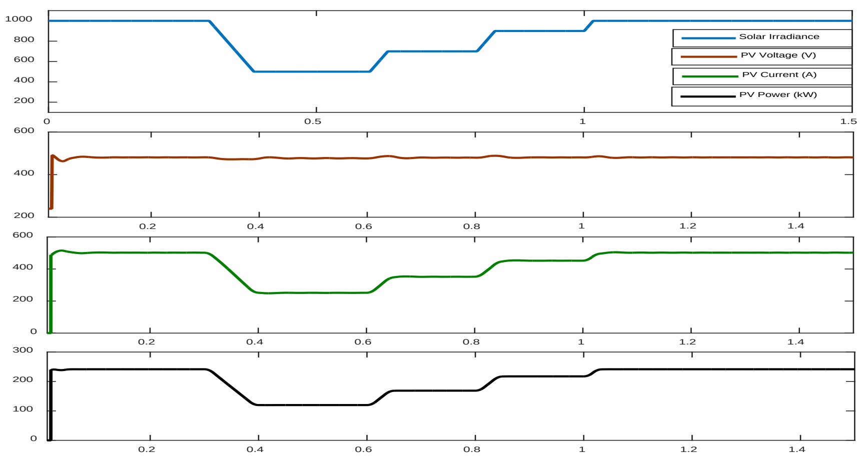

Figure 3. Voltage, Current, and Power Generation of proposed PV Array

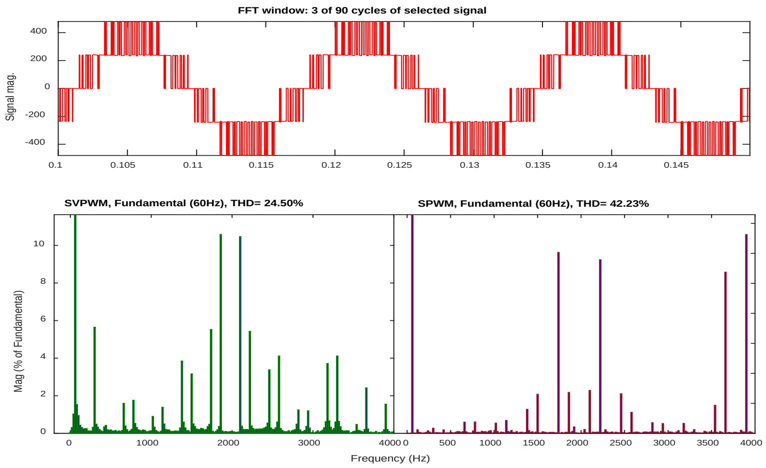

Figure 4. Comparative analysis of THD in SPWM and SVPWM

The comparative analysis based on the harmonic contents declares that space vector modulation produces less harmonic content which is a good sign to minimize switching losses. Due to the fact that space vector modulation produces less harmonics, simulation results are obtained only using SVPWM. The three-phase output from NPC inverter using SVPWM is shown in Figure 7. The three-phase 35 kV grid voltage is depicted in Fig. 8. Three-phase output of NPC inverter has maximum information in the fundamental component and can be connected to grid using LC filter and step up transformer.

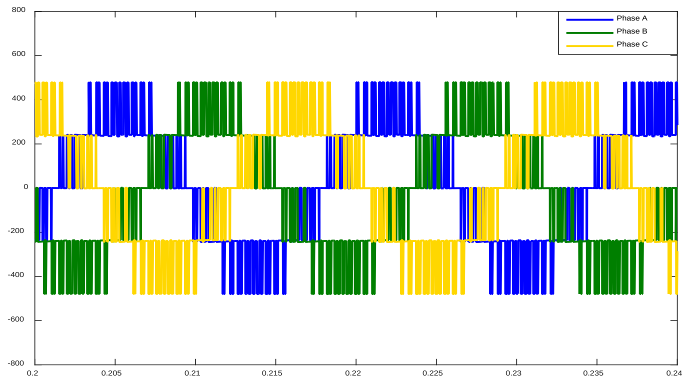

Figure 7. Three phase inverted voltage by NPC inverter

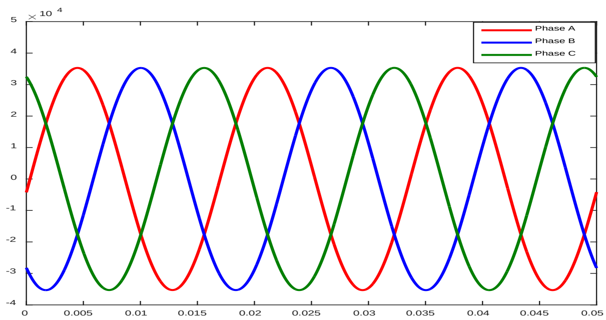

Figure 8. Three Phase AC grid voltage

5. Conclusion

This paper addressed the challenges of conventional power inverters and implemented the three level NPC inverter to improve inverter performance. Comparative analysis of sinusoidal and space vector PWM is performed in terms of harmonic components of output voltage of the inverter. Space vector modulation shows less harmonics. MATLAB / Simulink environment is used to perform the simulation of 250 kW solar PV array. For future works, EMI behavior and the EMI filter can be studied.

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Genişletilmiş Özet

Giriş

Enerji talebindeki artış, fosil yakıt fiyatlarının yükselmesi ve çevre kirliliğindeki üssel büyüme, temiz ve yenilenebilir enerji kaynaklarının büyük ölçekli entegrasyonuna gerek duyulmasını sağlamıştır. Yenilenebilir enerji kaynakları arasında yer alan solar Fotovoltaik (FV) enerji, geleneksel şebekelerin karşılaştığı zorlukları azaltmak için kullanılabilecek potansiyel enerji kaynaklarındandır. Solar FV uygulamaları temiz, çevre dostu ve bedava olması nedeniyle sürekli artış göstermektedir. Solar FV enerjisinin büyük faydalarına rağmen, DC-AC güç elektroniği dönüşüm devreleri güç kayıplarını artırmakta ve yerleşim yerlerindeki uygulamalarını kısıtlamaktadır. Bu nedenle, etkili güç dönüşüm topolojileri, güç çeviricilerdeki güç ve harmonik kayıplarını optimize etmek solar FV sisteminin en önemli ihtiyacı haline gelmiştir.

Metod

Önerilen sistem, Maksimum Güç Noktası İzleme (MGNİ) kontrol yöntemi, sinüzoidal Darbe Genişlik Modülasyonu (DGM), Uzay Vektör Modülasyonu (UVM), Nötr Nokta Kenetlemeli (NNK) inverter, 250 kW solar FV dizisi ve 15 kV AC şebeke kullanılarak çalıştırılmıştır. Geleneksel iki seviyeli dönüştürücünün aksine, önerilen üç seviyeli NNK inverter daha az harmonik, daha az Toplam Harmonik Bozulma (THB) üretir ve AC şebekeye güç iletimini artırır. Bu araştırmada NNK DC-AC inverter için 250 kW şebekeye bağlı solar FV dizisinde UVM yöntemi kullanılmıştır. Önerilen FV dizisi Simulink / MATLAB ortamında modellenmiş ve simüle edilmiştir. İstenen simülasyon sonuçları Simpowersystem ve Simelectronics alt programları yardımıyla gerçekleştirilmiştir. Daha önceki araştırmamızda tasarlanan artımlı iletkenlik MGNİ yönteminin güneş enerjisinden maksimum güç elde edilmesini sağladığı göz önüne alınmaktadır. 600-1000 W/m^2 arasında değişim durumunda, Solar FV dizisinden elde edilen MGNİ-tabanlı olarak maksimum DC güç doğrudan NNK inverterine uygulanır. Önerilen NNK inverterde, anahtarlama ve güç kayıplarını optimize etmek için sinüzoidal PWM ve uzay vektör PWM yöntemleri, IGBT güç anahtarlarının iletim süresini kontrol etmek amacıyla kullanılmıştır. Sinüzoidal DGM ve UVM'nin karşılaştırmalı analizi, harmonik bileşenler ve inverterin çıkış geriliminin THB'si baz alınarak gerçekleştirilmiştir. Simulink'in Hızlı Fourier dönüşümü (FFT) aracı, NNK inverterin istenen AC çıkış geriliminin harmonik içeriğini analiz etmek için kullanılmıştır. Önerilen NNK inverterinin AC çıkış gerilimi daha sonra 3 fazlı gerilim yükseltici transformatör yardımıyla 15 kV AC şebekeye bağlanmıştır. FFT analizi, uzay vektör modülasyonu yönteminin sinüzoidal DGM yöntemine göre THB ve güç kayıpları bakımından etkinliğini kanıtlamak amacıyla gerçekleştirilmiştir.

Sonuçlar ve Tartışma

Önerilen NNK invertere sahip 250 kW solar FV dizisi modelinin simülasyon sonuçları; solar FV dizisinin net güç üretimi, 250 kW FV dizisinin PV ve IV karakteristikleri, sinüzoidal ve uzay vektör modülasyonun karşılaştırmalı analizi, ve THB'ya dayalı karşılaştırmalı analizi değerlendirilmiştir. Önerilen şebekeye bağlı 250 kW solar FV sisteminde, modelin performans değerlendirmesi sonucunda uzay vektör modülasyonunun sinüzoidal PWM yöntemine göre etkinliği doğrulanmıştır.