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Performance Evaluation of Two-Level Photovoltaic Voltage Source Inverter Considering SPWM and SVM Switching Controller

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ABSTRACT
The switching control schemesincluding sinusoidal pulsewidth modulation (SPWM) and space vector modulation (SVM) are very important for the efficiency and accuracyof the voltage source inverter (VSI). Therefore, this paper presents a performance evaluation of a two-level VSI for the photovoltaic (PV) system based on adopted switching controllers namely, SPWM and SVM switching methods. The evaluation procedure and accuracy are demonstrated and investigated using simulations conducted for a 1.5 kW inverter in a MATLAB/Simulink environment. Two types of loads are utilized to assess the performance of the VSI which are resistive (R) load and resistive and inductive (RL) load. Total harmonic distortion (THD) is used for the comparison of the SPWM and the SVM. Results show that the SVM performs better compared with the SPWM in terms of THD rate. The THDs for SVM based system are found to be 0.02% and 0.08% for the R and RL, respectively; whereas the THDsfor SPWM controller are found to be 0.43% and 0.51% for the R and RL, respectively. Furthermore, mean square error (MSE) is also consideredas a statistical indicator. The MSE indicates that the SVM switching controller technique have superior outcomes compared with the SPWM switching controller technique and thus increases the efficiency of the whole system.

Keywords: Sinusoidal pulse-width modulation (SPWM), Space vector modulation (SVM), Twolevel voltage source inverter, Total harmonic distortion (THD), Photovoltaic (PV)

I. INTRODUCTION

The negative impact of fossil fuels leads to discover new energy sources like renewable energy resources (RER). The RER have become the major motive of the energy sector since they are free, clean, and environmental friendly [1].Fuel cell, wind turbine, and photovoltaic system (PVS) are considered as RES.The RES are considered significant because they have important benefits such asavailability around the globe, ensuing infinite energy supply, and pollutions-free maneuver[2]. Among the RER, the PVS seems to be the most significant part due to abundance of the solar resource where the earth received the solar energy from the sun ten times more than the total energy spend by the whole worldduring a year. Furthermore, the PVS can be used in rural areas and industrial power systems[3].However, an electronic device known as voltage source inverter (VSI) is important to connect the PVS to the load as the PVS can only produce DC power [4].The VSI must be able to supply high quality pure sinusoidal waveforms in the context of a standalone PVS.The VSI can be controlled by many ways.Each methodgenerates some distortion at the VSI waveforms.

Some of the power quality issues are voltage dips, noise, voltage flickers, and harmonics. The harmonics seems to be the main power quality issue [5]. Harmonics lead to equipment overheating, increasing of losses, and waveforms distortion [6]. The harmonic level of output waveforms of a system is determined by total harmonic distortion (THD) value. THD is highly depends on the pulse width modulation (PWM) switching scheme. Therefore, the VSI performance can be accomplished by applying a proper PWM switching scheme.

Numerous PWM have been mentioned in the literature such as carrier based pulse width modulation, third harmonic injection pulse width modulation, sinusoidal pulse width modulation, and space vector modulation. However, most widely used PWM switching techniquesare sinusoidal pulsewidth modulation (SPWM) and space vector modulation (SVM).The enhancement of the prototype PV inverter using the dSPACE DS1104 board was suggested in [7]. The proportional integral (PI) controller has been utilized to generate the switching signals to the insulated-gate bipolar transistor (IGBT) switching, therefore generating and adaptable the 50 Hz sinusoidal ACwaveforms.In [8], the SVM combined with voltage oriented control was applied to control the inverter for the PV system.Given that both techniques, SPWM and SVM, are recommended, therefore, this study is conducted to evaluate the performance of the VSI based SPWM and SVM techniques.

This paper comprises six sections. Section 2 depicts the voltage source inverter quality; voltage controller for PV inverter has been presented in section 3. The development of the sinusoidal pulse width modulation technique has been drawn in section 4; meanwhile the development of the space vector modulation technique has been described in section 5. The results have been discussed in section 6. Finally,the conclusion has been mentioned in section 7.

II. VOLTAGE SOURCE INVERTER QUALITY

One of the important power quality criterions for the inverter is the power quality. The VSI output waveforms must acquire low THD level. Inverter power quality is one of the problems due to the power conversion process [9].The electromagnetic phenomenon which describes the voltage or current in a certain time is referring to “power quality” (PQ)[10]. Grounded on this information, the loads may malfunction or not work at all at the presence of the PQ[11]. Therefore, the increase using of the RES in the future will leads to more research in the PQ field[11]. Preserving a good PQ is significant for the reliability of the loads. Thus, many PQ standards are recommended such as IEC61727, IEEE1547, IEEE519-1992, and EN61000-3-2 [12-14].

2. 1 Harmonics

The harmonic distortion(HD) is known as the voltage and current components with multiples of the fundamental frequency. Many problems can be occur due to the presence of harmonics such as; reduced power factor, malfunction of sensitive equipment, and premature failure of transformers.Therefore, in high-power applications, e.g. three-phase inverter system, low THD output waveform is important [15]. The THD is utilized to calculate the rate of the HD in an electrical power system. The THD for the voltage waveforms is expressed by (1) which is the percentage of voltage magnitude of all harmonic components to the voltage magnitude of the fundamental frequency [16].

$$THD_v = \frac{1}{V_1} \times \sqrt{\sum_{n}^{\infty} (V_n)^2} \times 100 \qquad (1)$$

where V_n is the n^{th} harmonic voltage in rms, and V_1 is the fundamental frequency voltage in rms.

2.2 Stability

Maintaining the stability of the system is a very important issue. Therefore, a suitable controller design is required whether the system is connected as a grid tie or as a stand-alone system. Two control designs have been found depends on the connected modes which are current control design and voltage control design. The current control design is usually used in grid connected mode; meanwhile voltage control design is used in stand-alone mode [17].

In current control mode, the aim is to regulate the current that the inverter supplies into the network[5]. In voltage control mode, it is significant that the inverter generates a proper voltage waveform wherethe voltage must be kept with fixed amplitudeand fixed frequency, irrespective of the load types [18]. Since the PV voltage source inverter is proposed for stand-alone system, therefore the voltage control mode is proposed in this work as will be mentioned in the next section.

III. VOLTAGE CONTROLLER FOR PV INVERTER

The archetype for the voltage controller for PV stand-aloneVSI is depicted in Fig. 1. It is consist from PVS, VSI, LC filter, voltage controller, and switching signaltechnique. The proposed voltage controller developed in this study is depicted in Fig.2 which also consists of two fuzzy logiccontrollers.

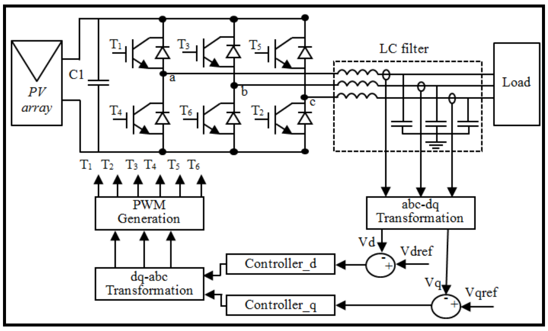

Fig.1. Block diagram of the stand-alone VSI

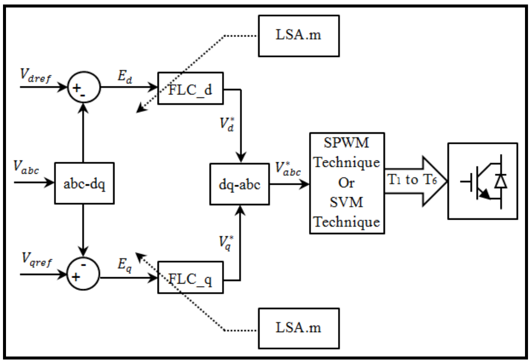

Fig. 2. The proposed voltage controller for the VSI

Three steps are required to implement the FLC which are fuzzification, inference engine design, and defuzzification[19].The time-consuming trial-and-error procedure utilized to tune membership functions (MFs) boundaries in the fuzzification step is the main weakness of FLC design. The poor performance in the system is possibly due to incorrect selection of MFs boundaries. Therefore, the lightning search algorithm (LSA) has been utilized to determine the MFs boundarieswhich start by resetting the number of iterations (T), dimension of the problem (D), step leader size (N), and channel time. More details about LSA implementation to determine the boundary values ofMFs can be found in [20].

Two types of switching controller have been used to evaluate the performance of two-level VSI. The first switching controller technique is the SPWM; meanwhile the second switching technique controller is the SVM which are the most important switching controller types. The next two sections will describe the development of these two switching controller techniques.

IV. DEVELOPMENT OF THE SINUSOIDAL PULSE WIDTH MODULATION TECHNIQUE

The SPWM is one of the most usedmethods that generate the switching signals to the IGBTs in order to produce the AC output voltage close to a sine waveform as possible [21].

In this study, the modulating signalof 50 Hz in the SPWM, (as in power system) is compared with the carrier signal of 5 kHz to produce the PWM signals for the power devices. The frequency of the triangular carrier signal creates the inverter switching frequency at which the power device, such as IGBTs, is switched. The PWM signals are created by comparing a sinusoidal reference signal (desired waveform) with a triangular carrier of frequency, *fc* that establishes a switching frequency. With PWM method, the VSI is able to achieve a sinusoidal output waveform [22].

The VSI output waveform is controlled by the control parameter known as modulation index, *MI*. The *MI* is the relationbetween the amplitude of reference signals, $V_{reference}$, and the amplitude of carrier signal, $V_{carrier}$which can be expressed as follows,

$$MI = \frac{A_{V_{reference}}}{A_{V_{carrier}}} \tag{2}$$

where $A_{V_{reference}}$ is the amplitude of reference signals and $A_{V_{carrier}}$ is the amplitude of triangular carrier signal. The *MI* will change by changing the amplitude of reference signals while keeping theamplitude of carrier signal constant. This leads to change the output line waveform because it is proportional to the *MI* as can be defined as follows,

$$V_{line,rms} = 0.612 \times MI * V_{dc} \tag{3}$$

where the V_{dc} is the DC-link voltage. The *MI* should be between 0-1 to work in line range. The output voltage will vary from 0 to 0.612 ofV_{dc}. The *MI*should keep below 1 for butter output waveform quality. The SPWM technique has been developed in MATLAB/Simulink as depicted in Fig. 3.

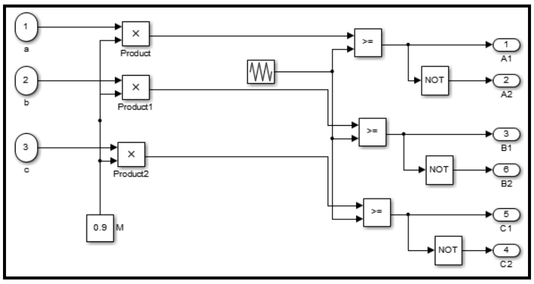

Fig. 3. The Developed model for the SPWM

V. DEVELOPMENT OF THE SPACE VECTOR MODULATION TECHNIQUE

The SVM is another important switching method. To extract sinusoidal AC waveforms from the VSI, the SVM is implemented in the inverter controlling[23].To implement SVM, the reference voltage, *abc*, is transformed into the *αβ* reference frame. The output signal resembles a hexagon consisting from six sections (V_1 to V_6.). The SVM control includes the *MI*, which is essential to enhance the performance by decreasing the THD of the inverter output waveform [24]. The *MI* is defined as,

$$MI = \frac{V_{p1}}{\frac{2}{\pi} V_{dc}} \tag{4}$$

where V_{p1} is the maximum fundamental voltage, and V_{dc} is the DC-link voltage [23]. The time shares are expressed as [25],

$$T_x = \frac{\sqrt{3} \cdot T_s \cdot |V_{ref}|}{V_{dc}} \sin\left(\frac{n}{3}\pi - \alpha\right) \quad (5)$$

$$T_y = \frac{\sqrt{3} \cdot T_s \cdot |V_{ref}|}{V_{dc}} \sin\left(\alpha - \frac{n-1}{3}\pi\right) \quad (6)$$

$$T_z = T_s - T_x - T_y \quad (7)$$

where $n = 1$ to 6 are the sectors at $0 \leq \alpha \leq \pi/3$; T_x, T_y, and T_z are the time vectors of the respective voltage vectors; α is the angle of the reference vector relative to the space vector, and T_s is the sampling time. The SVM technique that has been developed in MATLAB/Simulink is shown in Fig. 4.

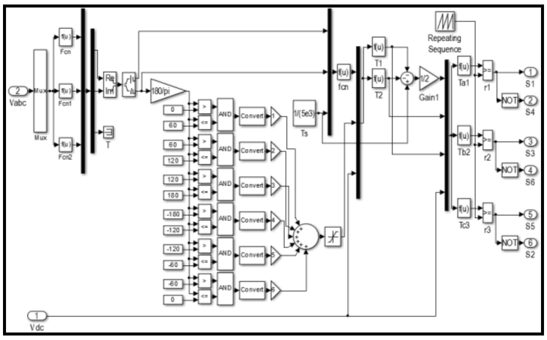

Fig. 4. The Developed model for the SVM

VI. RESULTS AND DISCUSSION

A 1.5 kW, 240 V, 50 Hz stand-alone PVS is developed in MATLAB environment as can be shown in Fig. 5 to evaluate the performance of the two-level VSI.Two types of the most important PWM techniques have been utilized to evaluate the performance of the VSI. The first technique is the SPWM; meanwhile the second technique is the SVM.

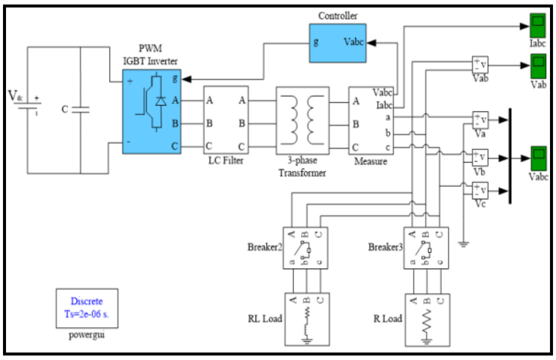

Fig.5. Simulation model for the two-level VSI

To analysis the performance of the VSI, fast Fourier transform (FFT) is applied on the VSI waveforms to verify their waveforms quality in terms of the THDfor two types of loads which are *R* and *RL* loads. The waveforms quality of the VSI is inversely proportional to the THD rate. Therefore, the goal is always to decrease the THD values as possible.

The voltage THD rates must be preserved and it should be less than 5% to comply with the IEEE Std 519-1992 international standard [14]. Fig. 6 and Fig. 7illustrate the THD rates of the voltages obtained for the *R* load and the THD are found to be 0.43% and 0.02% based SPWM and SVM, respectively.Bothtechniques, SPWM and SVM, achieved high quality waveforms where the THD are found to be much less than the 5% requirements of the IEEE Std 519-1992 international standard.

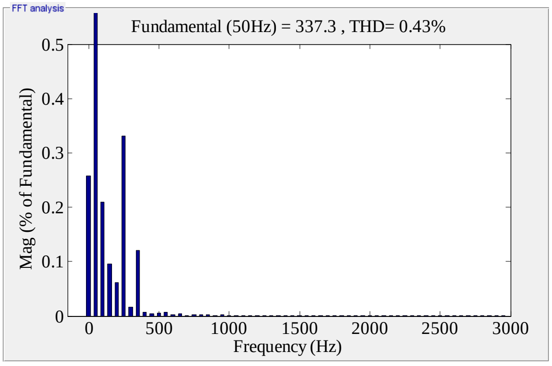

Fig. 6. THD for the voltage source inverter consideringSPWM with *R* load

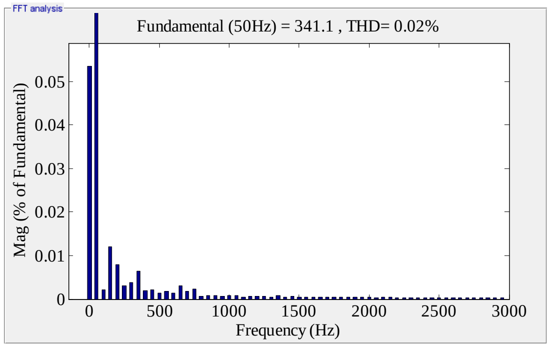

Fig.7. THD for the voltage source inverter considering SVM with *R* load

The THD have been also calculated for the VSI waveforms based SPWM and SVM when the system is connected to a*RL* load for more comparison. The THD values for the voltage waveform have been kept within a small percentage of 0.51% and 0.08% forSPWM and SVM, respectively as shown in Fig. 8 and Fig. 9.

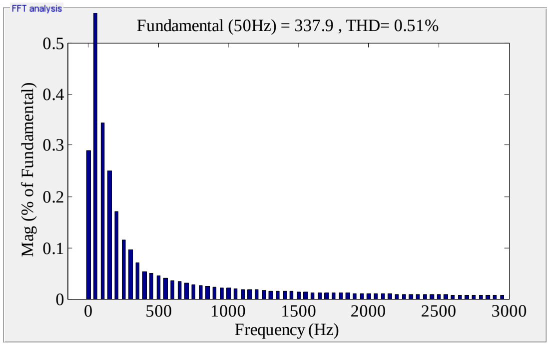

Fig. 8. THD for the voltage source inverter based SPWM with *RL* load

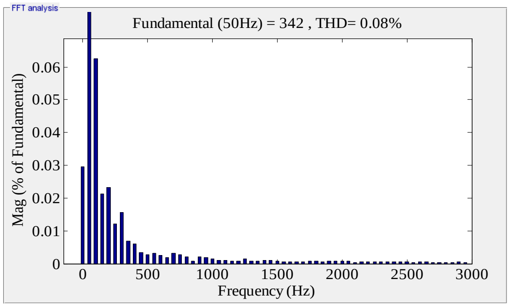

Fig. 9. THD for the voltage source inverter based SVM with *RL* load

The THD rates of SPWM and SVM are compared in Table 1. The table indicates that both of switching schemes can effectively deal with *R* and *RL* loads and produce clean waveforms which meet the IEEE Std 519-1992harmonic standard. However, the SVM show robust performance and superior quality compared with the performance of the VSI based SPWM.

Table 1. Simulation THD comparison of SPWM and SVM

Type of load	SPWM	SVM
R load	0.43%	0.02%
RL load	0.51%	0.08%

For further analyze the performance of VSI based SPWM and SVM, a statistical analysis was conducted by using the mean square error (MSE). MSE is inversely proportional to the quality of the VSI waveforms. An increase in MSE rate leads to decrease in the quality of the output waveform, whereas a decrease in the MSE value implies that the quality of output waveform is increase. The performance of VSI based SPWM and SVM technique in terms of MSE is illustrated in Fig. 10. The MSE values of the VSI based on SPWM and SVM with *R* load were found to be 0.00233 and 0.00170, respectively. Meanwhile the MSE for the output waveform with *RL* were found to be 0.00196 and 0.00132 for SPWM and SVM, respectively. These values clearly indicate that the SVM technique outperformed the SPWM technique in terms of MSE.

Fig. 10. Performance comparison of SPWM and SVM based MSE

VII. CONCLUSION

A performance evaluation of the SPWM and SVM switching controller technique based two-level VSI for the photovoltaic (PV) system has been investigated in this study. The system was developed in MATLAB/Simulink environment. Two types of loadswere utilized to evaluate the performance of the system which are *R* and *RL* loads. The comparison of the SPWM and SVM were conducted in terms of THD.The SVM achieved better performance than the SVM in term of THD where the THD values were found to be 0.02% and 0.08% with *R* and *RL*, respectively, meanwhile THD based SPWM were found to be 0.43%, and 0.51% with *R* and *RL*, respectively. Moreover, the quality of VSI waveform based SVM was found to be higher thanthe SPWM where the values of MSE using SVM have been found to be 0.00170 and 0.00132 with *R* and *RL* loads, respectively; whereas the values of the MSE were found to be 0.00233 and 0.00196 using SPWM with *R* and *RL* loads, respectively. Thus, it can be concluded that SVM based switching technique is better for VSI in order to obtain high quality output.

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