SIMULATION OF CASCADED H-BRIDGE MULTILEVEL INVERTER FOR GRID CONNECTED PHOTOVOLTAIC SYSTEM USING DSAE PWM

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ABSTRACT

A single-phase Cascaded H-bridge eleven level inverter for grid-connected photovoltaic system was developed in this paper. The discrete sine area equalization pulse width modulation technique was used for modeling. The particle swarm optimization algorithm was used for eliminating the harmonic distortion. The performance of the inverter was found to be better for the discrete sine area equalization pulse width modulation technique. The harmonic spectrum and output waveforms for various load conditions were obtained for both DSAE PWM and OHSW-PWM techniques. It was also found that DSAE PWM technique can handle load variations by maintaining total harmonic distortion.

KEYWORDS: Multilevel Inverter, Cascaded H-bridge Inverter, Total Harmonic Distortion, DSAE PWM, SHE-PWM, MATLAB

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1. INTRODUCTION

In the recent years, the demand for clean and green energy requires high quality output power with low switching losses. It is also seen that the soft switching technology develop showing that the demand further increases by improving efficiency. This trend is expected to continue in coming years because the energy produced by renewable sources is expected to satisfy 20% and 50% of the total needs in 2020 and 2050 respectively. It is also witnessed that among these renewable energy sources, solar photovoltaic energy is found to be a promising energy.

An important consequence of this situation is a change of the electric power system from the present one, consisting of a relatively low number of very high power ac generators, to a distributed one, characterized by an extremely large number of small and medium power dc and ac generators supplied by renewable energy sources connected to the grid through electronic power converters, the latter adapting the produced energy to grid specifications.

This new scenario introduces many technical, economic, and political challenges because it is changing the way in which the electrical energy resources (generation, transmission and distribution networks) are designed and managed. From the technical viewpoint, the use of electronic power converters introduces new and challenging issues, including increased topological complexity, additional power losses, and electromagnetic interferences, thus reducing the overall quality of service, efficiency, and network stability.

Franquelo and Rodriguez [1] introduced the pulse width modulated (PWM) multilevel inverter is an effective alternative to current inverter topologies and provides an introduction of the modeling techniques and the most common modulation strategies. Lai and Peng [2] have described three recently developed multilevel voltage

source converters and the techniques to balance the voltage between different levels in multilevel converters. Rodriguez, Lai and Peng [3] have described the most relevant control and modulation methods developed for this family of converters: multilevel sinusoidal pulsewidth modulation, multilevel selective harmonic elimination, and space-vector modulation. Tolbert and Peng [4] have experimentally demonstrated that traditional 2-level high frequency pulse width modulation inverters for motor drives have several problems associated with their high frequency switching and two different multilevel topologies are identified for use as a converter for electric drives. Rodriguez and Dixon [5] have introduced the PWM regenerative rectifiers with reduced input harmonics and improved power factor. In early stages, multilevel active rectifier were employed mainly in high-voltage high-power industrial and traction applications because they distribute the applied voltage among a number of cascaded power devices, thus overcoming their voltage limits and allowing the elimination of output transformers in medium-high voltage systems. Since their output voltage is a modulated staircase, they outperform two-level PWM inverters in terms of total harmonic distortion (THD), without the use of bulky expensive and dissipative passive filters has been demonstrated in [6,7]. Multilevel inverters in the field of renewable energies, including photovoltaic (PV) generators has been described in [8, 9]. Calais and Agelidis [10,19] have developed Unipolar SPWM full-bridge with transformer less grid connected inverter, a lot of depth researches, where new freewheeling paths are constructed to separate the PV array from the grid in the freewheeling period.

Ertl and Kolar [11] have proposed a novel multicell DC-AC converter for applications in renewable energy systems. Alonso and Sanchis [12] have introduced a new control method and proportional PWM modulation of the cascaded H-bridge multilevel converter for grid-connected photovoltaic systems and this control makes each H-bridge module supply different power levels, allowing therefore for each module an independent maximum power point tracking of the corresponding photovoltaic array. Walker and Sernia [13] have proposed an alternative topology of nonisolated per-panel dc-dc converters connected in series to create a high voltage string connected to a simplified dc-ac inverter and buck, boost, buck-boost, and Cuk converters are considered as possible dc-dc converters that can be cascaded. Rahiman and Kumar [14] have developed a fifteen level cascaded H-Bridge Configuration, equal dc voltages are selected for each of the units, with step modulation and fundamental frequency switching which has reduced conduction loss and switching loss. Kang and Park [15] have developed multilevel PWM inverters suitable for the use of stand-alone photovoltaic power grid-connected inverters for photovoltaic modules. Alepuz [16] have described a three level inverter that can be used to interface distributed dc energy sources with a main ac grid or as an interface to a motor drive. Ozdemir and Tolbert [20] have proposed a five level DMLI fundamental frequency switching strategy for three phase stand-alone photovoltaic systems by selecting the switching angles such that the lower order harmonics are eliminated. Besides being able to maximize the power obtained from the PVAs, the multilevel converter usually presents the advantages of reducing the device voltage stress, being more efficient and generating a lower output voltage harmonic distortion. Among the following three main families of multilevel converters; diode-clamped, capacitor-clamped and cascaded H-Bridge, the latter is usually considered in the literature for PV applications [17,18].

Fortunato [21] have proposed an improved maximum power point tracking with better performance to solve a fast changing irradiation problem. Shanthi.B [22] have proposed multilevel inverter control strategies are implemented in real time using FPGA for linear and non-linear loads. Shuitao yang [23] have introduced H_∞ controller with explicit robustness in terms of grid-impedance variations to incorporate the desired tracking performance and stability margin. F.T. Josh [24] have proposed multilevel inverter in the field of renewable energies, reduces output filter dimensions and influence of perturbations caused by cloud darkening or seasonal variations. Jun Mei, Bailuxiao [25] have proposed an improved phase

disposition pulse width modulation (PDPWM) for a modular multilevel inverter which is used for Photovoltaic grid connection to achieve dynamic capacitor voltage balance without the help of an extra compensation signal. Lewicki & Morawiec [26] suggested a control strategy of DC-link voltages for a seven-level CHB inverter. In this method SVM strategy has been used to generate the output voltage vector properly but the DC-link voltages are not balanced.

Closed loop operation of OHSW-PWM technique can maintain the modulation index of the output voltage up to an extent. However, this method failed to maintain the THD with the load variations and fundamental rms output voltage. The single-phase cascaded H-bridge eleven level inverter for a grid-connected photovoltaic system with discrete sine area equalization pulse width modulation technique has been modeled and analyzed for estimating various responses.

2. CASCADED H-BRIDGE INVERTER TOPOLOGY

Figure 1: Block diagram of Cascaded H-bridge inverter topology with DSAE PWM

The block diagram of a proposed CHB inverter topology with DSAE PWM is shown in figure 6.6. This system consists of several PV modules, DC/DC power converter, a multilevel DC/AC power inverter and a filter. The PV modules arrangements are considered with multi-string technology. Each string of the PV array is connected to DC/DC boost converter with MPPT. As the irradiance level is inconsistent throughout a day, the amount of power generated by the PV modules is always changing with weather conditions. The P&O algorithm is used to extract maximum power from PV array. The DC power from the PV array is boosted using DC-DC boost converter with DC bus capacitors. The output of these converters is the DC power supply of the multilevel DC/AC power converter. The output of eleven level inverter is AC voltage, which is connected to grid system utility feeder through filtering inductor. The injected current must be sinusoidal with low harmonic distortion. The power factor is also maintained at near unity. PSO algorithm is employed for optimizing non-linear objective function and finding out the optimal switching angles for the MLI switches. The objective of DSAE PWM is to eliminate lower order harmonics. The DSAE PWM with closed loop control using PSO algorithm has been simulated using MATLAB software.

Figure 2: Cascaded h-bridge inverter topology for grid connected pv system

A schematic diagram of CHB inverter topology of grid connected PV system is shown in figure 6.1. The CMLI topology consists of 'n' number of H-bridge inverters connected in series. Each DC-link is fed by a short string of PV panels. By considering cells with the same DC-link voltage, the inverter can synthesize an output voltage V_{HT} with 'n' levels. This high-quality voltage enables the reduction of the harmonics in the generated current, reducing the filtering effort at the input. This topology can inject sinusoidal input currents with unity power factor to the grid, even under conditions of unequal solar radiation of the string of PV cells. The CMLI is connected to grid through inductance filter, which is used to reduce the switching harmonics.

3. MODELING ON DSAE PWM

The Discrete Sine Area Equalization PWM technique is capable of handling load variations while maintaining THD. The concept behind this technique is to equalize the area under the multilevel output voltage to that of the area under the sine waveform of the desired fundamental voltage at discrete time periods. For different load variations, a linear equation is formulated in such a way that sine area gets equalized with the multilevel output voltage area and by solving that equations the respective time periods t_{i1} , t_{i2} are obtained. The time periods t_{i1} , t_{i2} can be controlled to achieve the different area under the output voltage which is directly proportional to the maximum value of the fundamental voltage.

The switching angles for the proposed DSAE PWM technique is designed by using the basic electrical equations related to the alternating current. Generally, the entire system can be divided into four steps.

First step in the proposed methodology is to finding out the discrete time periods in which the sine area and the multilevel inverter output voltage area is made to be equal. As shown in the fig. 1, the discrete time periods t_i is the time at which sine waveform reaches the multilevel inverter input DC source voltage V_{dc} where i represents each level of the multilevel inverter. The time periods t_i is calculated by using the following equations.

$$V_i = V_m \sin(\omega t) \quad (1)$$

V_i is the instantaneous voltage of the sine wave, V_m is the maximum voltage of the desired sine waveform, ω is the angular frequency of the desired sine waveform. The equation (1) can be rearranged to obtain the discrete time periods.

$$t_i = \frac{\sin^{-1}\left(\frac{V_i}{V_m}\right)}{\omega} \quad (2)$$

In the above equation (2) V_i is substituted with the respective V_{dc} for different levels. Hence V_{dc} is assumed to be constant for all the five H-bridge circuits. So, for each level, the instantaneous voltage would be

$$V_i = V_{dc} * i \quad (3)$$

Second step is to find out the area under the sine waveform between the discrete time periods $t_{(i-1)}$ and t_i , the area under the curve is obtained by integrating the sine waveform between the respective time periods.

$$A_i = V_m \int_{t_{i-1}}^{t_i} \sin(\omega t) \quad (4)$$

Where A_i is the segmentation area which is the area under the sine curve between the time periods $t_{(i-1)}$ and t_i .

With the segmentation area founded out, the next step is to find out the t_{i1} and t_{i2} such a way that the segmentation area equals to the area under the multilevel inverter output voltage at the time periods t_i . In order to find out t_{i1} , t_{i2} , a system of two linear equations are formulated and by solving that the time periods t_{i1} and t_{i2} are obtained.

$$V_{dc} * (i-1) * t_{i1} + V_{dc} * i * t_{i2} = A_i \quad (5)$$

$$t_{i1} + t_{i2} = t_i - t_{i-1} \quad (6)$$

In the equations (5) and (6), A_i and t_i are founded out from the previous steps and V_{dc} is the constant input DC source voltage. t_{i1} and t_{i2} are the unknowns to be found. As the above linear system has two unknowns and two equations, it can be converted in to matrix form as follows.

$$A t = \begin{pmatrix} V_{dc} * (i-1) & V_{dc} * i \end{pmatrix} \begin{pmatrix} t_{i1} \\ t_{i2} \end{pmatrix} \quad (7)$$

$$B = \begin{pmatrix} A_i \\ t_{i1} + t_{i2} \end{pmatrix} \quad (8)$$

where A is the Input matrix and B is the output matrix.

From the above matrices, the following matrix equation (9) is formed, Where X is the unknown to be found out.

$$X = At^{-1}B \quad (9)$$

By solving the equation (9), unknown's t_{i1} and t_{i2} is obtained.

$$X = \begin{pmatrix} t_{i1} \\ t_{i2} \end{pmatrix} \quad (10)$$

Finally, the switching time α_i is calculated with t_{i1} and t_{i2} values using the equation.

The switching time α_i are calculated only for half cycle of the output voltage because of the switching time will be same for both negative and positive half cycle (quarter wave symmetry). The switching time α_i can be applied to the no-load condition, but if the load gets increased in the circuit which increases the current and voltage drop in the source impedance of the circuit. This leads to decrease in the output voltage from the desired output voltage. The percentage deviation in output voltage from the desired voltage is called Modulation Index m.

$$m = \frac{V_o}{V_d} \quad (11)$$

V_o is the output voltage at the inverter load side, V_d is the desired output voltage at the load side. As a voltage source, multilevel inverter should maintain modulation index at unity for different load variations. In order to achieve that, the output voltage is continuously measured at the load side and modulation index is calculated. If the modulation index is not at the unity, then the switching time is again calculated from the Step 3 by substituting $V_{dc} = V_{dc} * m$ in the equation (5). The new switching time regains the voltage and maintains the modulation index. This process continuously monitors and maintains the modulation index at unity.

4. PARTICLE SWARM OPTIMIZATION ALGORITHM

The particle swarm optimization (PSO) algorithm has been employed for estimating the switching angles θ_1 , θ_2 , θ_3 , θ_4 and θ_5 which will lead to the 5th, 7th, 11th and 13th lower order harmonics elimination in a multilevel inverter. An objective function is used for this purpose. This function uses the set of five trigonometric transcendental equations containing the switching angles θ_1 , θ_2 , θ_3 , θ_4 and θ_5 .

5. SIMULATION RESULTS

The open loop and closed loop topology of cascaded h-bridge eleven level inverter topology using DSAE PWM are carried out using MATLAB/Simulink software. The elements and the parameters considered for simulation are presented in Table 1 for the cascaded h-bridge eleven level inverter topology for grid connected PV system for various load conditions. The system is simulated with a switching frequency of 5 kHz. The PSO algorithm is developed and simulated wave forms of output voltage, output current and total harmonic distortion are shown for open loop and closed loop response.

Table 1: Parameters of the Cascaded H-Bridge Inverter

Symbols	Parameters	Values
S_i	Solar Insolation	1000W/m ²
T	Temperature	25°C
N_c	Number of cells per module	36

N_{ps}	Number of Parallel strings	66
N_{ss}	Number of series connected modules per strings	11
f_s	Switching frequency	5KHZ
V_g	Grid Voltage	230V
$V_{o(pv)}$	PV array output voltage	36V
f_f	Filter fundamental frequency	50HZ
C	DC link capacitor	2200 μ f
L	Load Inductor	10mH
R_L	Load resistor	10 Ohm
N	Number of Levels	11

Figure 3: Simulation model of grid connected PV system

The Simulation model of grid connected PV system is shown in fig.3. The output voltage of the PV array is obtained by load current based on the solar irradiation level. The output voltage waveform of the PV array is shown in Fig.4. The PV output of 36V is obtained by adjusting the temperature value. The PV array is connected with boost converter. The boost converter helps to improve the voltage gain observed by the PV array.

Figure 4: Output voltage waveform of PV Array

MPPT technique is used for maximum energy tracking from the Sun, so for this purpose various maximum power point tracking methods are used. Here perturb and observe algorithm is used so that the sign of the last perturbation and the sign of the last increment in the power are used to decide what the next perturbation should be. If there is an increment in the power, the perturbation should be kept in the same direction and if the power decreases, then the next perturbation

should be in the opposite direction and the algorithm is implemented. The process is repeated until the MPP is reached. Then the operating point oscillates around the MPP.

Figure 5: Output Voltage Waveform of MPPT DC/DC Converter

The output voltage waveform of MPPT DC/DC converter is shown in Fig.5. The output voltage depends upon the input voltage and this MPPT is suitable for improving the voltage level from 130 V.

Figure 6: PWM signals for DC/DC Boost Converter

The PWM signals for DC/DC boost converter is shown in fig.6. The boost converter is permitted to work in continuous mode and the multilevel inverter switching sequence uses DSAE PWM technique. The duty cycle varies from 0 to 1.

Figure 7: Input DC voltage from grid connected PV system

The output from the PV array is unregulated and so boost converter is used to regulate the dc output. The switches

used involve switching losses thereby decreasing the efficiency. The regulated dc input voltage from grid connected PV system is 65.95V and it is given to the five h-bridge levels of the proposed cascaded h-bridge eleven level inverter topology. It is shown in fig.7.

Figure 8: PWM signals for Cascaded h-bridge eleven level inverter

The PWM signals for cascaded h-bridge eleven level inverter are shown in fig.8. PWM generators are used in control of both eleven level cascade H-bridge multilevel inverter and boost converter.

Figure 9: Output voltage waveform of Cascaded h-bridge eleven level inverter

The output voltage and output current of cascaded h-bridge eleven level inverter has eleven levels. The fundamental frequency of inverter is 50 Hz. Due to parallel connection, voltage obtained is around 330V are shown in fig.9.

Figure 10: Output current waveform of Cascaded h-bridge eleven level inverter

The output current of cascaded h-bridge eleven level inverter is 0.6A is shown in fig.10. The output current depends upon the connected load. For finding the switching angles, it is suitable to use the Fourier coefficients technique to eliminate some harmonics. The number of harmonics to be eliminated is equal to the number of switching angles are obtained. The percentage of THD variations with variable load are shown in fig.11 and 12. The total harmonic distortion of cascaded h-bridge eleven level inverter output current is around 21.04% for conventional method and 8.22% for proposed

method. Fig. 13. illustrates the grid voltage and the injected current to the grid during the balanced operating condition. The power factor is around 0.99 and the current THD is very near to the IEEE-519 constraints.

Figure 11: Harmonic spectrum of the inverter output current (OHSW PWM)-Conventional method

Figure 12: Harmonic spectrum of the inverter output current (DSAE PWM)-Proposed method

Figure 13: Grid voltage and Grid current are in phase at unity power factor

6. CONCLUSIONS

The Cascaded h-bridge multilevel inverter with DSAE PWM has been modeled and simulated using MATLAB for estimating the performance under various responses. It has been found from the simulated and experimental results that the

cascaded h-bridge eleven level inverter with DSAE PWM perform better than conventional method (OHSW PWM) since it provides output with low distortion and higher fundamental RMS output voltage. It may be concluded that the Cascaded h-bridge multilevel inverter based DSAE PWM technique can maintain the output voltage across the load side with reduction in total harmonic distortion.

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