

Model predictive control of single phase grid connected multilevel inverter

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This paper presents a single phase seven-level inverter grid connected photovoltaic (PV) system application. The proposed system consists of a PV arrays, a single phase seven-level inverter interface and single phase power grid. The control of the inverter is based on a model predictive control algorithm where the main aim is to control the injected power which is produced by the PV source, to improve the quality of the current waveform, to reduce the THD of the current and to ensure the elimination of the shift phase between the injected current and the grid voltage in order to fulfill the requirement of the smart grid network. To clarify the advantages of the application of the model predictive control to the proposed topology, simulation results using MATLAB/SIMULINK and real time simulations using dSPACE 1103 are provided in this paper.

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1. Introduction

In a world where environmental protection and energy conservation are growing concerns, the research goes toward smart grid to a chive these requirements. Smart power grid is modernized, more efficient way to distribute electricity to save energy and money and improve reliability of the grid. It is also designed to link the grid to large scale solar and wind projects that are built far away from the cities and suburbs where people need electricity.

One of the main resources in smart grid is solar cell which is used in the photovoltaic system. This system has been recently become an essential target overall the world. It can be found in many applications such as power stations, building power supply, transportation, standalone devices, rural electrification, and roadway electrification. There are many PV power systems ranging from 100 W to several megawatts. As the solar cell generates a DC power, a power interface circuit is required to invert the DC voltage to AC voltage and also to suit the frequency and voltage level to the load requirement.

In the recent years, there has been a great interest in multilevel inverters (MLIs) technology, including single-phase voltage-source inverters [1]-[5], where their topologies are being used in PV systems due to their advantages over the conventional two level inverters. Indeed the series connection of the power converter modules allows reducing the voltage stress of each converter module (or increases the voltage capability of the overall converter structure). Besides, the resolution of the staircase waveform of the output voltage increases with the number of voltage steps of capacitor voltage sources available in the multilevel inverter. As a result of

the improved resolution in the voltage harmonic content, filtering efforts and the level of the Electromagnetic Interference (EM) generated by the switching operation of the converter can be reduced.

With the introduction of multilevel voltage source converters, various modulation techniques have been developed with pulse width modulation (PWM) [6]-[8]. PWM has been studied extensively during the past decades. Different techniques in PWM have been developed to achieve less THD, easy implementation and less computation time. Their implementation in the design of ac drive systems depends on the load requirement, the power level, and the semiconductor devices used in the power converter. The switching harmonics are suppressed to a large extent by the low-pass characteristic of the machine inductances.

Model Predictive Control (MPC) is a different approach which considers a model of the system in order to predict the future behavior of the system over a horizon in time [9]-[13]. A cost function represents the desired behavior of the system. It has emerged as a very powerful method for the control of electrical energy using power converters. MPC is very intuitive and easy to apply, even in the presence of nonlinearities. In addition, it can avoid the use of linear controllers and modulators [14],[15]. Moreover, the multivariable case can be easily considered by this control [16]. Microprocessors and Digital Signal Processors (DSP) have been used for MPC of the inverter system. Using microprocessors give the system flexibility in modifications.

In this paper, MPC for single phase grid connected is proposed to control on the single phase multilevel inverter. Although the proposed control method is valid for any

type of multilevel inverter, a seven-level inverter has been chosen to prove the idea. The system is simulated while operating synchronous and transferring various power values to the grid. The measured THD values of the output current are quite low. The system provides good performance as a PV energy conversion system.

2. The configuration of the complete system

Fig. 1 shows the base configuration of the complete system which consists of photovoltaic module, multilevel module, H-Bridge inverter, filter and single phase grid. The base configuration of the multilevel inverter generates seven-level output voltage. Moreover, this topology can be expanded to any number of levels.

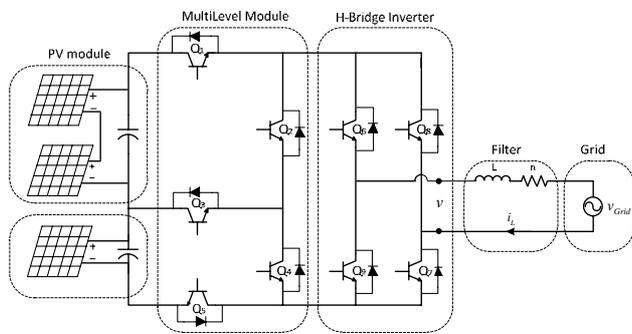


Fig. 1 configuration of the complete system.

2.1 Principal of operation for multilevel module

The multilevel inverter principle presented in this paper is explained through Fig. 2 [17]. Consider that the input voltage is V_{dc} for the two terminals below and the double voltage for the upper two terminals. If the desired output voltage between the terminals A and B is V_{dc} , the switches Q_3 and Q_5 should be turned ON and the diode D_{Q2} is turned ON as shown in Fig.2 (a). Moreover, if the desired output voltage which is required between terminals A and B is $2V_{dc}$, the switch Q_1 should be turned ON and the diodes D_{Q3} and D_{Q4} are turned ON as shown in Fig.2 (b). In addition to this, if the desired output voltage between terminals A and B is required to be $3V_{dc}$, the switches Q_1 and Q_5 should be turned ON. From the last three steps the desired output voltage between terminals A and B has four levels $0, V_{dc}, 2V_{dc}$ and $3V_{dc}$

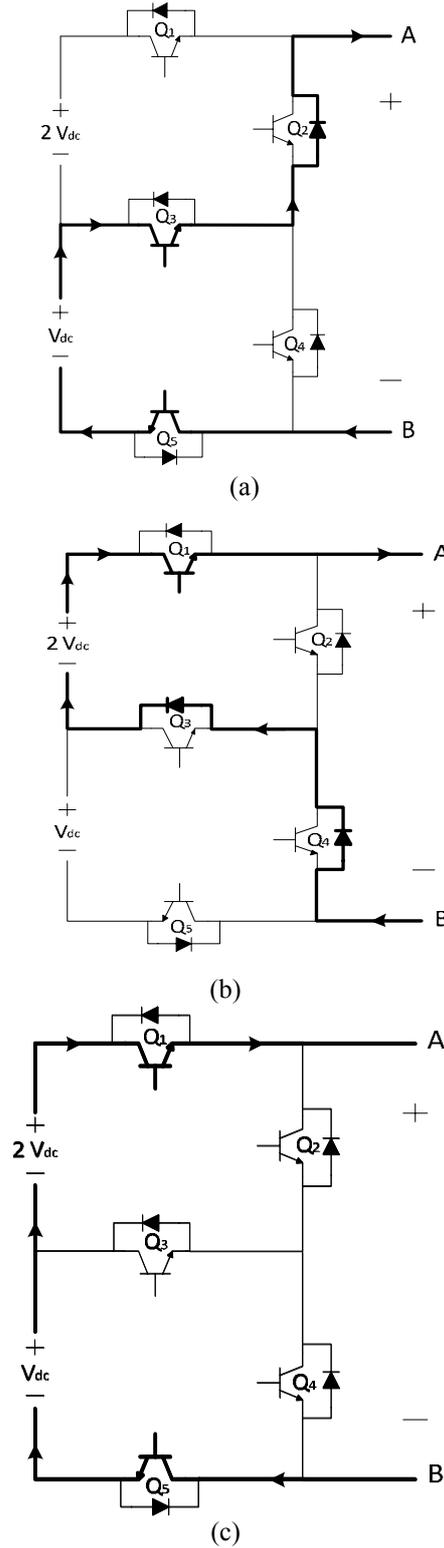


Fig. 2. States of the switches for different output voltage levels.

2.2 H-bridge module

In cascaded H-bridge there are four switches that are operating with low switching frequency to reduce the switching loss in a switch. The switching frequency of these switches is 100Hz. When the voltage of the grid is

positive, switches Q_6 and Q_7 should be switched ON. Moreover, when the voltage of the grid is negative, switches Q_8 and Q_9 should be switched ON. Table I lists the summary of the output voltage levels possible for the complete states in multilevel inverter. State condition "1" means the switch is ON and "0" means the switch is OFF.

Table 1. The output voltage level and switching states

Voltage	Switch State								
	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9
$V_3=3V_{dc}$	1	0	0	0	1	1	1	0	0
$V_2=2V_{dc}$	1	0	0	0	0	1	1	0	0
$V_1=1V_{dc}$	0	0	1	0	1	1	1	0	0
$V_0=0$	0	1	0	1	0	1	0	1	0
$V_{-1}=-V_{dc}$	1	0	0	0	1	0	0	1	1
$V_{-2}=-2V_{dc}$	1	0	0	0	0	0	0	1	1
$V_{-3}=-3V_{dc}$	0	0	1	0	1	0	0	1	1

3. System modeling

The propose system presented in this paper is shown in Fig. 1. It is obvious that the used single phase multilevel inverter has seven states as shown in Table 1. The actual value of the load current at t_k can be measured. On the other side, based on the measured value the load current at t_{k+1} can be predicted according to the following expressions:

$$v = L \frac{di_L}{dt} + r_L i_L + v_{Grid} \quad (1)$$

$$L \frac{di_L}{dt} = L \frac{i_L(t+1) - i_L(t)}{T_s} \quad (2)$$

$$i_L(t+1) = \left(1 - \frac{r_L T_s}{L}\right) i_L(t) + \frac{T_s}{L} (v(t) - v_{Grid}(t)) \quad (3)$$

Where i_L is the inductor current, $i_L(t+1)$ is the predicted value of the inductor current for the next step, T_s is the sampling period, L is the inductance and r_L is the ESR for inductor.

The proposed cost function which can fulfill the requirements of the presented model can be expressed as follows:

$$g = \lambda \left| i_{ref}^*(t) - i_L(t+1) \right| \quad (4)$$

Where $i_{ref}^*(t)$ is the reference current at this time, which is inphase with the grid voltage. λ is the weighting factor which is equal to one in this case.

To generate the reference current, a grid voltage is sensed then divided on the maximum value of the grid voltage which is equal to $220\sqrt{2}$ or $110\sqrt{2}$ V. The maximum value of the required current which has to be injected to the grid is equal to the reference power divided by the maximum value of the grid voltage multiplied by two. The selection process of the optimal switching states in each sampling time step is presented in the flowchart shown in Fig. 3.

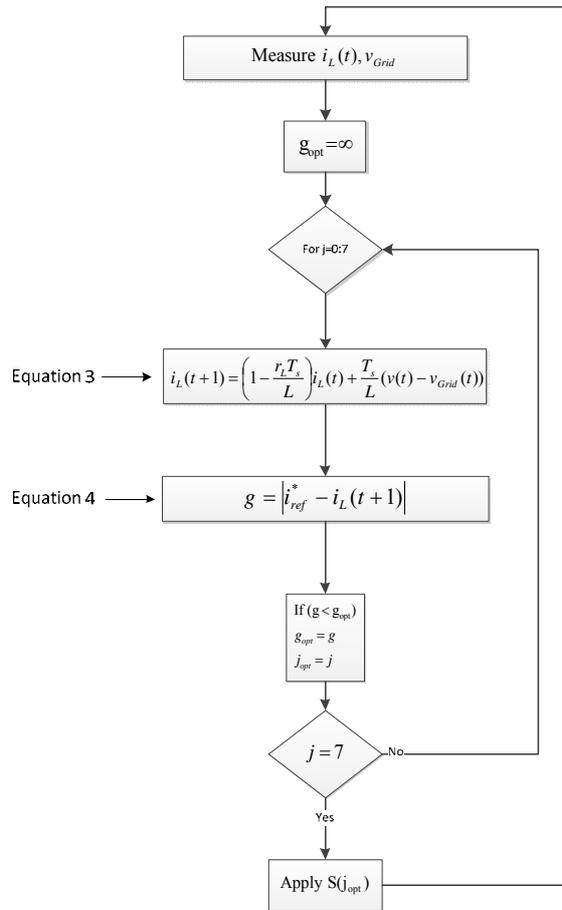


Fig. 3. Flow diagram of the model predictive control for seven-level multilevel inverter.

4. Implementation

The model predictive control strategy which is applied on the seven-level multilevel inverter presented in this paper is implemented based on a dSPACE DS1103 and MATLAB/Simulink[®]. The sampling period used in this control is $T_s = 2\mu s$. The inductance of the inductor filter is 1mH with an ESR of 500m Ω . The implemented control algorithm based on the dSPACE DS1103 is explained in details in the flow chart which is presented in Fig. 3. The voltage of the solar cell is equal to 110V. In the upper two terminals, two PV modules are connected in series so that the voltage is 220V_{dc}. Moreover, the lower two terminals are connected to one PV module which voltage is 110V. The reference power is changed from 1KW to 1.3 KW.

Fig.4 shows the output voltage of the multilevel inverter at the input side of the filter. It is clear that the output voltage is depending on the levels of the used topology. In the present paper a seven-level multilevel inverter is used to prove the idea of the control.

The goal of the control is to inject sinusoidal current to the grid with unity power factor. As shown in Fig. 5 the current injected is inphase with the grid voltage with unity power factor. Moreover, a step change of the reference power is changed from 1KW to 1.3KW shows that the

injected current changes with high response as shown in Fig. 5 (b).

Following to the standard limits presented in Table 2 [18], the THD of the current should be less than 5% at rated inverter output current. Moreover, each individual harmonic should be limited to the percentages listed in Table 2. The limits in Table 2 are a percentage of the fundamental frequency current at full system output. Even harmonics in these ranges should be less than 25% of the odd harmonic limits listed. Fig. 6 shows the curve of the THD with various powers. In case of light load the THD is higher than 5% but if the power increases the THD will be reduced. So it is preferable to make this system work under a power not less than 600W. Fig. 7 shows the spectrum analysis at 1.2KW for the current injected to the grid. It is obvious that the 3rd order is very small.

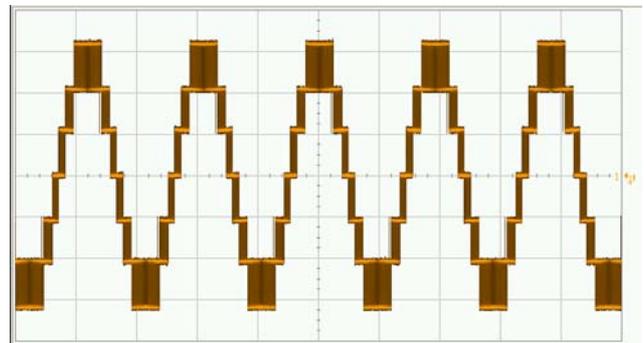
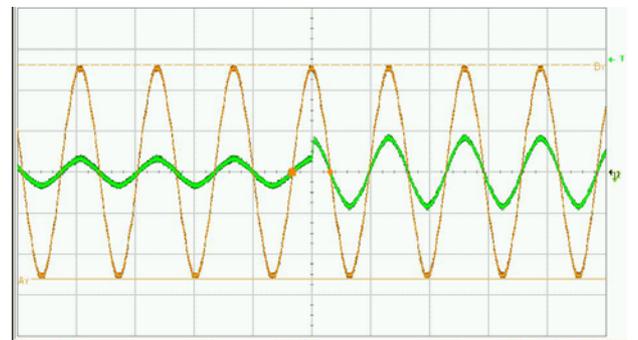
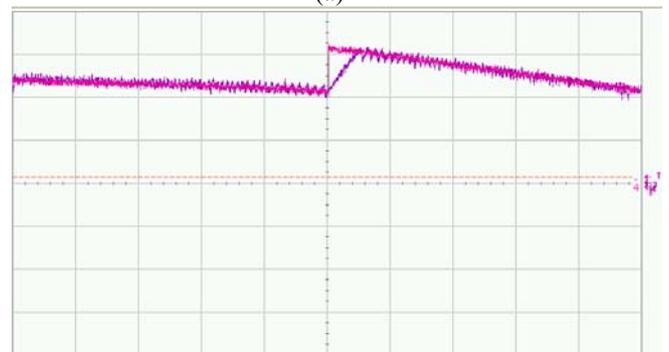


Fig. 4 The output voltage of the multilevel seven-level inverter



(a)



(b)

Fig. 5 (a) The injected current and the grid voltage (b) Detail of the reference step, showing the injected current when the power is changed from 1KW to 1.3KW

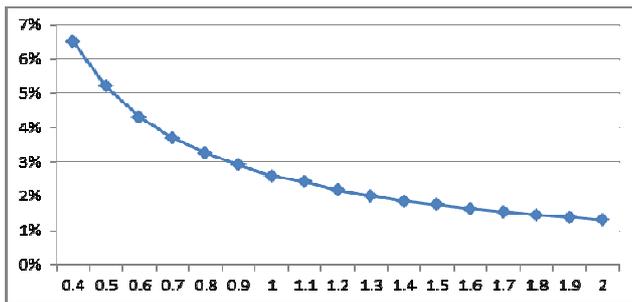


Fig. 6 The value of the total harmonic distortion (THD) versus output power to the grid.

Table 2 Distortion limits as recommended in IEEE Std 519-1992 for six-pulse converters [17].

Odd harmonics	Distortion limit
3 rd -9 th	<4.0%
11 th -15 th	<2.0%
17 th -21 st	<1.5%
23 rd -33 rd	<0.6%
Above the 33 rd	<0.3%

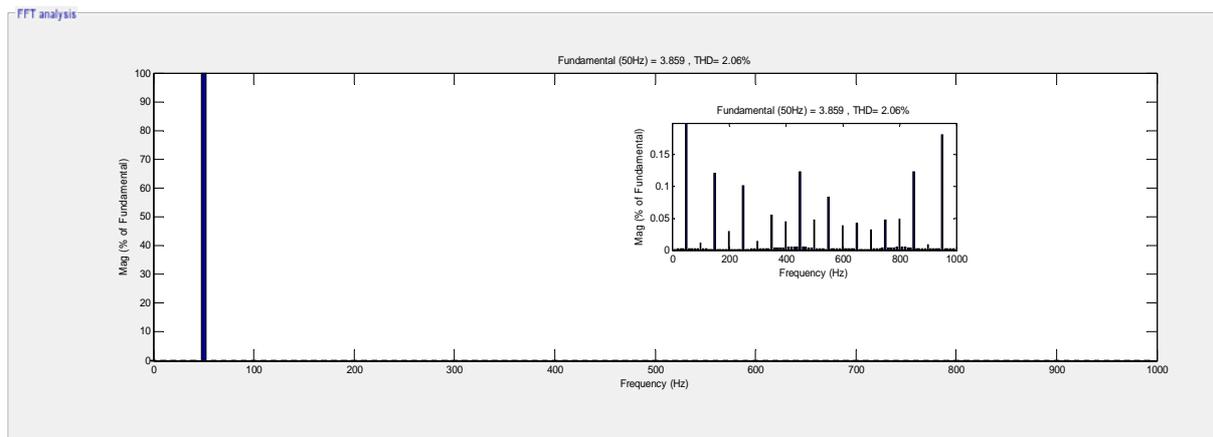


Fig. 7 Spectrum analysis at 1.2KW and THD is 2.06%

5. Conclusions

This paper deals with the model predictive control of a single phase multilevel inverter, where the main aim to track the reference current which is varying up the change of the load current. The obtained results show that the used control method allows to the injected current to the grid to have a sinusoidal waveform following the recommended standard limits under unity power factor with high dynamic performance. As it has been explained, the MPC method does not require any kind of linear controller or modulation technique compared to the other control methods so far used for controlling the single phase multilevel inverter. On other side, this paper shows that the model predictive control of multilevel inverter presented in this paper is a promising control with high reliability and flexibility.

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References

- [1] José Rodríguez, Jih-Sheng Lai, Fang Zheng Peng, IEEE Transactions on Industrial Electronics, **49**(4), 724 (2002).
- [2] Sung-Jun, Park, Feel-Soon Kang, Man Hyung Lee, Cheul-U Kim, IEEE Transactions on power electronics **18**(3), 831 (2003).
- [3] V. G. Agelidis, D. M. Baker, W. B. Lawrance, C. V. Nayar, , 1997. ISIE '97., Proceedings of the IEEE International Symposium on Industrial Electronics **2**, 589 (1997).
- [4] B.P. McGrath, D.G. Holmes, Industrial Electronics, IEEE Transactions on , **49**(4), 858 (2002).

- [5] J. Holtz, Proceedings of the IEEE , **82**(8), 1194 (1994).
- [6] J. Holtz, Power Electronics Specialists Conference, PESC '92 Record, 23rd Annual IEEE, **1**, 11 (1992).
- [7] A. Nabae, S. Ogasawara, H. Akagi, A novel control scheme for PWM controlled inverters, IEEE/DIS Ann. Meet., Toronto, Canada, 1985, pp. 473-478.
- [8] J. Holtz, P. Lammert, W. Lotzkat, High-speed drive system with ultrasonic MOSFET PWM inverter and single-chip microprocessor control, IEEE Trans. Industry Applications, pp. 1010-1015, 1987.
- [9] J. Rodríguez, J. Pontt, C. Silva, P. Correa, P. Lezana, P. Cortés, U. Ammann, IEEE Transactions on Industrial Electronics, **54**(1), 495(2007).
- [10] S. Kouro, P. Cortés, R. Vargas, U. Ammann, J. Rodríguez, IEEE Transactions on Industrial Electronics, **56**(6), 1826 (2009).
- [11] P. Cortés, A. J. Wilson, J. Rodríguez, IEEE Transactions on Industrial Electronics, **56**(8), 2691 (2010).
- [12] R. Vargas, U. Ammann, B. Hudoffsky, J. Rodríguez, P. Wheeler, IEEE Transactions on Power Electronics, **25**(26), 1426 (2010).
- [13] M. Morari, J. H. Lee, Computers and Chemical Engineering, **23**, 667 (1999).
- [14] P. Cortes, M. Kazmierkowski, R. Kennel, D. Quevedo, J. Rodriguez, Industrial Electronics, IEEE Transactions on, **55**(12), 4312 (2008).
- [15] H. Abu-Rub, J. Guzinski, K. Krzeminski, H. Toliyat, IEEE Trans. on Industrial Electronics, USA, **51**(3), 585 (2004).
- [16] Jose Rodriguez and Patricio Cortes, Predictive Control of Power Converters And Electrical Drives, John Wiley & Sons, 2012.
- [17] M. Mousa, M.E. Ahmed, M. Orabi, Telecommunications Energy Conference, 2009. INTELEC 2009. 31st International, pp.1-6, 2009.
- [18] IEEE Std 929-2000, IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems, Institute of Electrical and Electronics Engineers, Inc., New York, NY.

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