❏   1524

Predictive Direct Power Control (PDPC) of Grid-connected Dual-active Bridge Multilevel Inverter (DABMI)

H.H. Goh[1], Azuwien Aida[2], S.S. Lee[3], S.Y. Sim[4], K.C. Goh[5]
[1,2,4,5] Department of Electrical Power Engineering, Universiti Tun Hussien Onn Malaysia
[3] School of Electronics and Computer Science, University of Southampton Malaysia Campus, Malaysia

Article Info	ABSTRACT
	This paper deals with controlling a grid-connected dual-active bridge multilevel inverter for renewable energy integration. The concept of direct power control is integrated with model predictive control algorithm, which is termed as predictive direct power control, to control the real and reactive power injected into the power grid. The proposed multilevel inverter allows more options of feasible voltage vectors for switching vector selections in order to generate multilevel outputs, and thereby obtaining high power quality in the power grid. By using the predictive direct power control, simulation results show that the proposed multilevel inverter produces lower power ripple and manage to achieve currents with low total harmonic distortion which are well within the IEEE standard. The modeling and simulation of the system are implemented and validated by MATLAB Simulink software.

Corresponding Author:

H. H. Goh
Department of Electrical Power Engineering,
University Tun Hussein Onn Malaysia,
86400 Parit Raja, Batu Pahat, Johor, Malaysia.
Email: hhgoh@uthm.edu.my

1.   INTRODUCTION

Developments in renewable energy (RE) integration are getting to be distinctly essential as worldwide need affordable, reliable, and clean energy. In recent years, renewable energy sources are used to fill the developing energy claim. The expansion in industrialization has increasing the energy demand. It is widely known that the biggest energy request is provided by the fossil fuels. Nonetheless, the induced air pollution as well as the expanding cost of fossil energy have made it important to look towards renewable energy sources as a future energy solution. Therefore, the integration of renewable energy resources with the grid has prompted significant researches in power electronic converters for energy conversion [1].

Power quality (PQ) issues have turned out to be essential problems for power consumer at all level of utilization. Electrical power quality is a wide field which covers power systems engineering, from transmission and distribution, to end client issues. Approximately 70 to 80% of all the related power quality problems are attributed to faulty connections. There are various categories of PQ issues, namely the power frequency disturbances, electromagnetic interference, transients, harmonics and low power factor. Among all of these problems, current harmonics are one of the most dominant concern which is worth emphasized.

To date, one of the popular approaches for controlling the performance of power system is by utilizing the power electronic interfaces. Some common control parameters usually involve frequency, system voltages, current harmonics, active and reactive power. A proper selection of power converter is important in order to work as a good interface between the grid and renewable energy sources. However, interconnection of renewable sources into the grid is generally a new development which is very challenging due to the intermittent characteristics of the renewable energies, particularly the wind and photovoltaic

energy which are highly dependent on the unforeseen climate change. This may bring about abundance variety of voltage or frequency of the grid and further deteriorate the quality of the grid. In this regard, the control of power electronic converter which can synchronized to the grid and efficiently maintain the power quality of the system become exceptionally important [2].

The control of grid connected voltage source converter has attracted much attentions nowadays. Generally, control methods can be broadly classified into two categories, i.e. the direct and indirect control methods. Voltage Oriented Control (VOC) is a type of indirect control technique which is mostly used to control the voltage source converter. On the other hand, direct power control (DPC) is one of the most popular direct control strategies in grid connected inverter. This technique is derived from the concept of direct torque control (DTC) from which in each sampling period, an optimal voltage vector is selected from a look-up table in order to push the state of the system towards the reference value. The main drawback of DPC strategy is the use of hysteresis controller that caused variable switching frequency and hence dispersed harmonic spectrum. In addition, it suffers from poor reference tracking with large power ripples. Predictive Direct Power Control (PDPC) can be viewed as an extension of DPC by replacing the switching table with predictive vector sequence selection. PDPC approach has been employed in order to overcome the drawbacks in DPC strategy [3].

Adoption of efficient controllers for the system alone is not enough, different topologies of converters also have great impact on the system performance. The various multilevel inverters presented in literature have been generally perceived as interesting solutions to enhance the voltage limits to a desired level. Therefore, multilevel inverter (MI) has the merit of low current total harmonic distortion (THD) with closely sinusoidal output current waveforms and lower switching losses [4]. The induced low harmonics and low power ripple are very important since it may prevent, or at least reduce the costs arisen in power losses and bad functioning of equipment from either the consumers or electrical distribution system. In this instance, this work proposes the implementation of a type of MI, termed as dual-active bridge multilevel inverter (DABMI) as the grid connected converter. The concept of advance PDPC control strategy is adopted to control power quality issues of the proposed DABMI for renewable energy integration.

2. DUAL-ACTIVE BRIDGE MULTILEVEL INVERTER TOPOLOGY

Compared to other cascaded MIs, the dual-active bridge multilevel inverter (DABMI) topology has received little attention despite its simplicity of fault-tolerant capacity [5]-[6]. As the name implies, it comprises two inverters cascaded in the form shown in Figure 1. It is reliable because its outputs can be short-circuited when there is damage in either one of the cascaded inverters. In this regard, DABMI is functioning as a standard two level three-phase inverter [7]. The two isolated dc sources are used to cut the path of common-mode current flow and to achieve multilevel voltage waveforms [8]. Note that both the cascaded inverters use equal number of transistors which allow the DABMI to imitate and produce voltages similar to waveforms generated by a two-level, a three-level or a four-level inverter based on the possible switching states and active vectors [9]-[10].
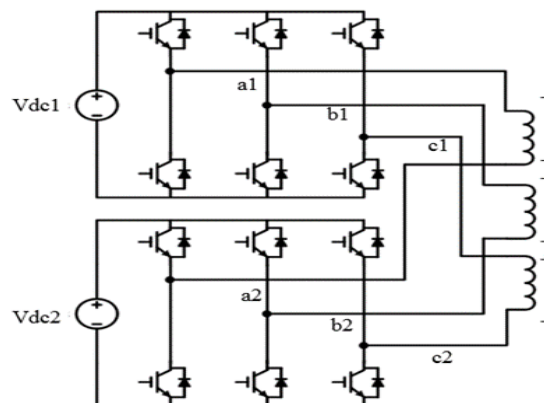

Figure 1. Dual-active bridge multilevel inverter

The merits of DABMI are also pronounced when it is compared to other type of MI. For instances, it does not require fast recovery clamping diodes and immune to neutral point fluctuations experienced by the neutral point clamped multilevel inverter (NPCMI) configuration. When compared to flying capacitor multilevel inverter (FCMI) topology, DABMI uses less capacitors [11] and hence getting rid of complicated capacitor control. On the other hand, it also uses fewer isolated dc supply than H-bridge converters [12]-[14] and less diodes than NPCMI [15].

3.   PREDICTIVE DIRECT POWER CONTROL OF A DUAL-ACTIVE BRIDGE MULTILEVEL INVERTER

3.1. System Description

This work is putting emphasis on DABMI topology with PDPC control, as presented in Figure 2. The standard two level inverters with a total of twelve switches work in a complementary manner to avoid short circuit. On the other hand, apart from isolating the load from the system, the three-phase transformer also serves to match the voltage levels to the grid. The primary transformer is fed by the two cascaded inverters while the secondary transformer is connected to the RL loads which are connected to the power grid. The series equivalent resistance is considered in the circuit and function to acquire more accurate control of power. Modulation scheme is nonessential in this control approach since the PDPC itself will generate the possible switching state to produce switching pattern. The effectiveness of minimizing harmonics current, power ripple and precise power tracking has been proven by the performance of PDPC [16].

The most basic and fundamental requirement for multilevel inverter with grid connected applications is to keep the inverter synchronized with the grid while ensuring appropriate power supply regardless of the variation of frequency, amplitude and phase in grid voltages. Synchronization unit has been acknowledged to be a compulsory part for grid connected converter [17]. Power and reactive power can be directly control by using PDPC while eliminating the use of phase lock loop (PLL) [18]. It is also proved to be a promising alternative to provide the synchronization between the grid and inverter with low computational burden and low complexity.
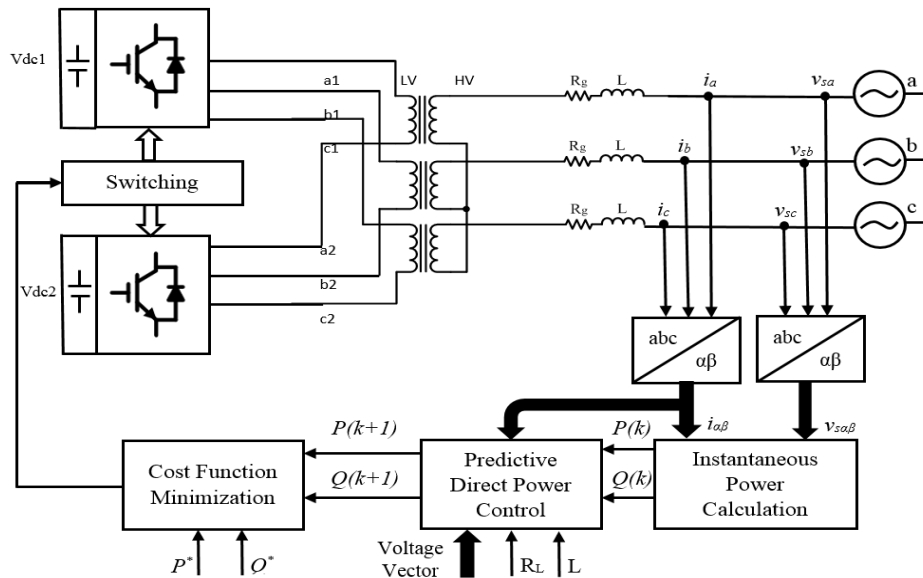

Figure 2. PDPC Control Block Diagram of a DABMI

3.2. Predictive Model of Grid Connected DABMI

The grid voltage component vs and phase current component i, are transformed from the natural abc reference frame to the stationary reference frame by using the magnitude invariant Clarke Transformation, which is given by

$$P = \frac{2}{3} \begin{bmatrix} 1 & -\dfrac{2}{3} & -\dfrac{1}{2} \\ 0 & \dfrac{\sqrt{3}}{2} & -\dfrac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \chi_a \\ \chi_b \\ \chi_c \end{bmatrix}$$

(1)

The dynamic input current of the converter can be expressed as

$$v_{s\alpha\beta} = L\frac{di_{\alpha\beta}}{dt} + R_L i_{\alpha\beta} + v_{c\alpha\beta}$$

(2)

Where $v_{s\alpha\beta}$ denotes the grid voltage, $i_{\alpha\beta}$ denotes the phase current, and $v_{c\alpha\beta}$ denotes the output voltage of inverter all in $\alpha\beta$ frame. The respective derivative of phase current component can be determined by rearrangement of (2).

$$\frac{di_\alpha}{dt} = \frac{1}{L}\left(v_{s\alpha} - v_{c\alpha} - i_\alpha R_L\right)$$

$$\frac{di_\beta}{dt} = \frac{1}{L}\left(v_{s\beta} - v_{c\beta} - i_\beta R_L\right)$$

(3)

The magnitude invariant instantaneous active power P and reactive power Q are defined as

$$P = \frac{3}{2}(v_{S\alpha}i_\alpha + v_{s\beta}i_{s\beta})$$

$$Q = \frac{3}{2}(v_{s\beta}i_\alpha + v_{s\alpha}i_\beta)$$

(4)

The resulting dynamic model of active and reactive power are

$$\frac{dP}{dT} = \frac{1}{L}\left(v_{s\alpha}^2 + v_{s\beta}^2 - v_{s\alpha}v_{c\alpha} - v_{s\beta}v_{c\beta} - R_L P\right) - \omega_s Q$$

$$\frac{dQ}{dT} = \frac{1}{L}\left(v_{s\alpha}v_{c\beta} - v_{s\beta}v_{c\alpha} - R_L i_\alpha v_{s\beta} - R_L Q\right) - \omega_s P$$

(5)

Discretization of (5) enable the calculation of the predicted active power and reactive power at the next sampling instant, $P(k+1)$ and $Q(k+1)$

$$P(k+1) = P(k) + \frac{T_s}{L}\left[\frac{3}{2}\left(v_{sa}^2(k) + v_{sb}^2(k) - v_{sa}(k)v_{ca}(k) - v_{sb}(k)v_{cb}(k)\right) - R_L P(k)\right] W_s T_s Q(k)$$

$$Q(k+1) = Q(k) + \frac{T_s}{L}\left[\frac{3}{2}\left(v_{sa}(k)v_{cb}(k) - v_{sb}(k)v_{ca}(k)\right) - R_L Q(k)\right] - W_s T_s P(k)$$

(6)

It is worth emphasized that both $P(k+1)$ and $Q(k+1)$ depend not only on the grid parameters but also taken into account the grid frequency. The evaluation of (6) is necessary to predict the optimum voltage vector. The quadratic cost function which measures the deviation between the reference power and the predicted power is defined as

$$g = \left[P^* - P(k+1) \right]^2 + \left[Q^* - Q(k+1) \right]^2 \tag{7}$$

where P* represents the reference active power and Q* represents the reference reactive power.

4.   SIMULATION RESULT

In order to verify the feasibility of the proposed system, the PDPC of grid connected DABMI has been simulated using MATLAB/ Simulink Software. The system parameters used in simulation are shown in Table 1.

Table 1. System Parameter

Description	Variable	Value
Rated Power	P	5kW
DC Voltage 1	Vdc1	300V
DC Voltage 2	Vdc2	150V
Transformer voltage rating	Tx	500/500V
Sampling Time	Ts	50e-6s
Line Voltage Frequency	f	50Hz
Inductance	L	9e-3H
Equivalent series resistance of inductor	R_L	0.14Ω

In DABMI, each inverter consists of two voltage level and six phase legs, which constitutes 64 feasible switching states. However, there are only 37 unique voltage vectors for selection due to the redundancy of switching states, as shown in Figure 3. As a result, the DABMI is able to generate more possible switching states. The output voltages can hence be stepped in smaller increment and permit lower total harmonic distortion with lower switching frequency and thus reduce the switching losses.

The reference active power, P*of this system is set to 5000W and the reference reactive power, Q* is kept at zero. The output power and reactive power illustrate in Figure 4 shows that the proposed controller manage to keep the active and reactive power close to their references. Low active and reactive power ripple, which are approximately 100W and 106VAR respectively, are identified with lower current harmonics established in the system.
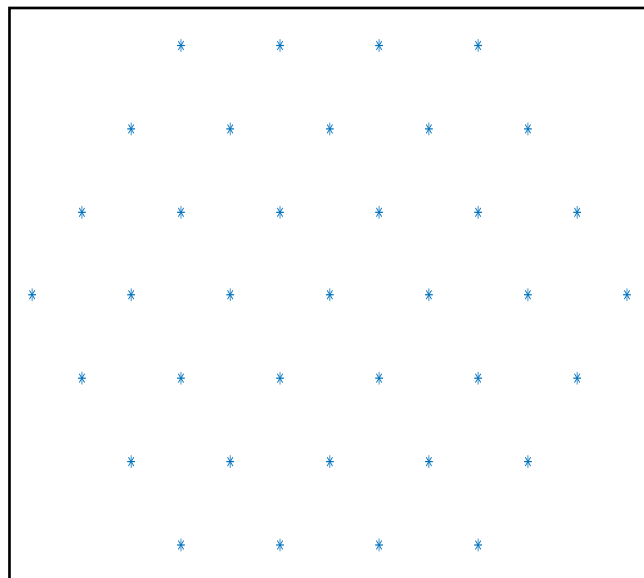

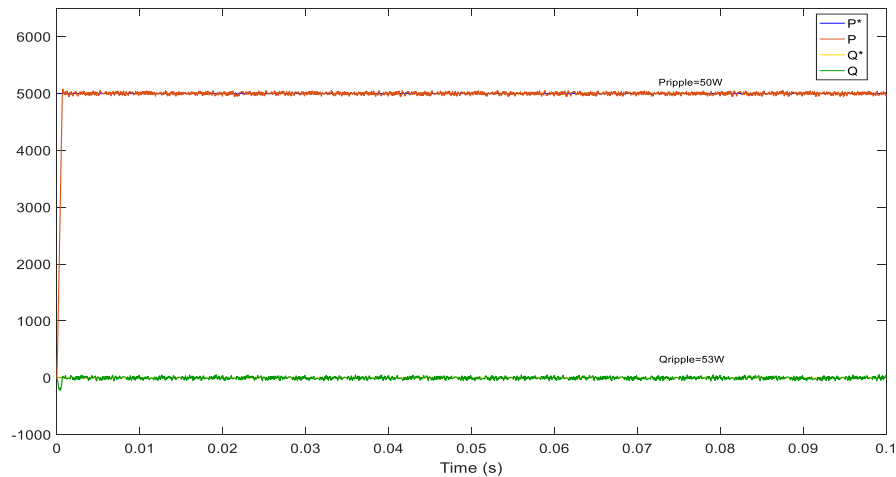Figure 3. Voltage Vector of DABMI

Figure 4. Output power (P) and reactive power (Q) of DABMI

It is apparent from Figure 5 that the DABMI achieves its peak voltage ratings of $\frac{2}{3}Vdc$, i.e. 200V. It is also proved that the proposed PDPC can perform the multilevel operation for dual- active bridge multilevel inverter. The performance of the three phase output currents is presented in Figure 6 which illustrates the sinusoidal line current with peak amplitude of 28A out of phase with each other by 120°. Figure 7 shows the grid voltage and current are in phase for phases, a, b and c. Hence, it shows good agreement with Figure 4 that the reactive power is zero. Hence, the PDPC is verified to be functionaing properly without the need of grid synchronization module such as PLL. Harmonic spectrum current of phase a, b and c in Figure 8 – Figure 10 shows excellent value of total harmonic distortion (THD) of the proposed system, to be specifically, 0.63% for phase a, 0.67% in phase b and 0.63% of phase c has been achieved, which is within the IEEE standard 519.
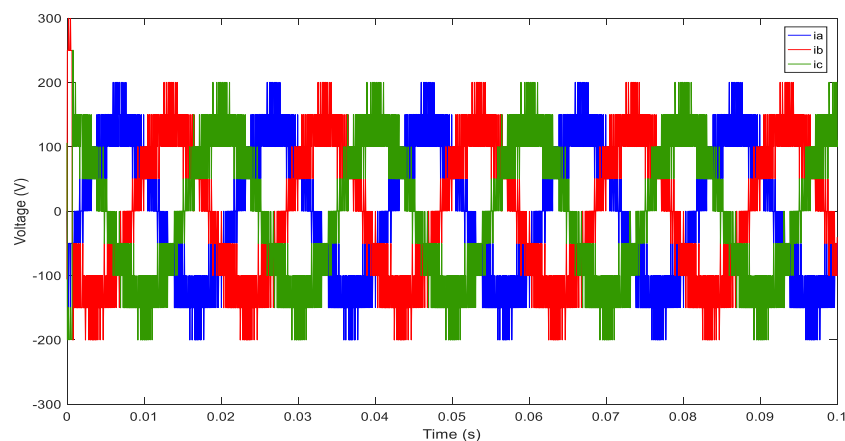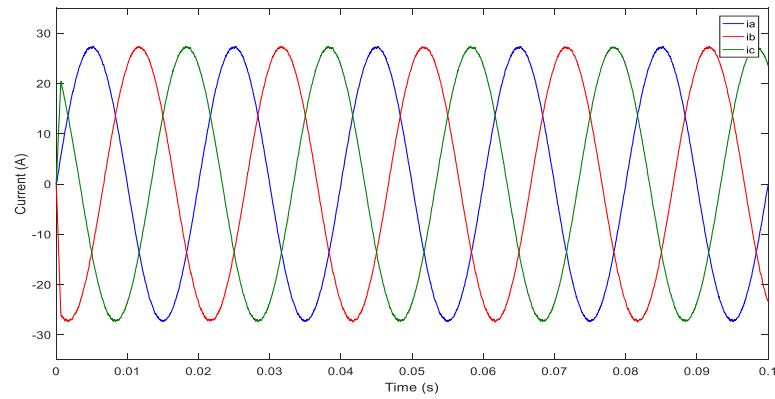
Figure 5. Output voltage of DABMI
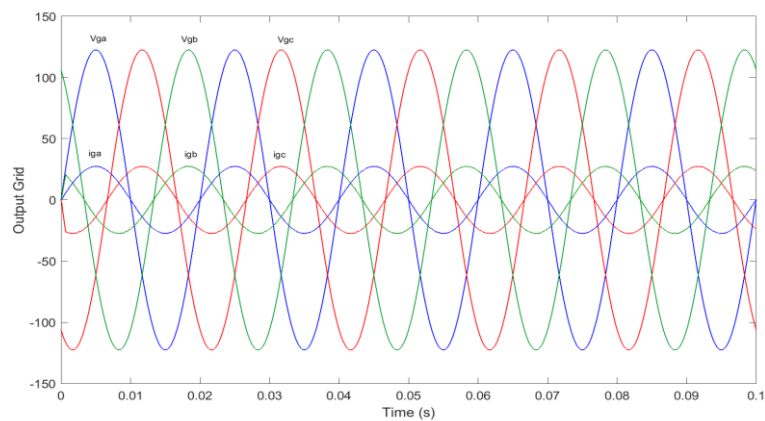
Figure 6. Output current of DABMI

Figure 7. Grid current and voltages
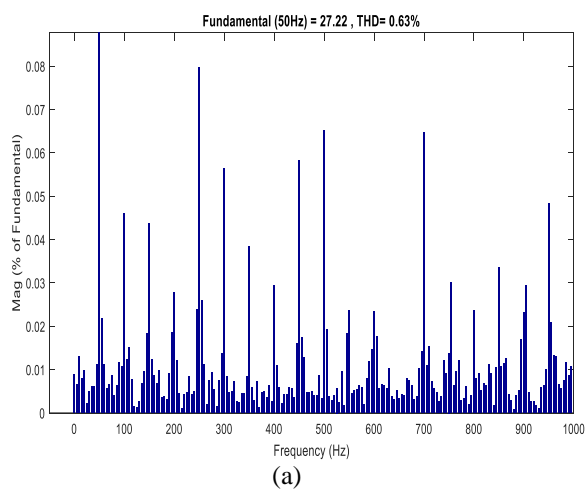

(a)

Figure 8. Harmonic spectrum current of phase a
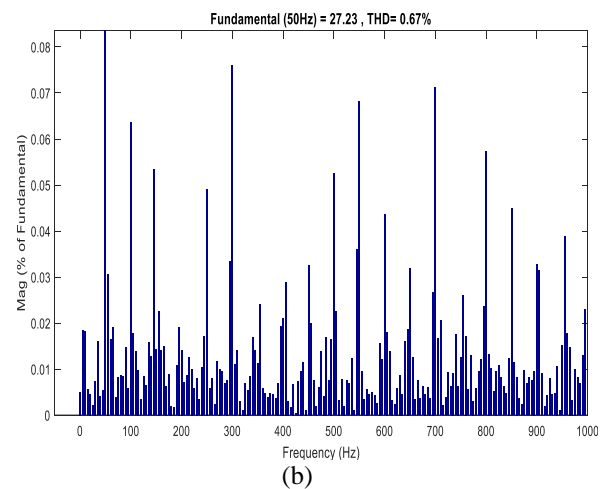

(b)

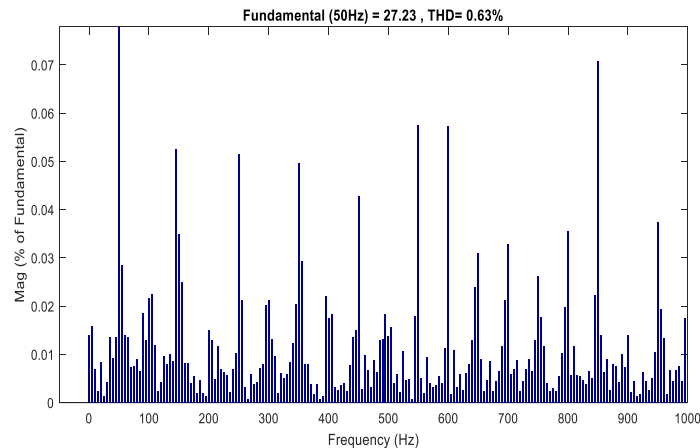Figure 9. Harmonic spectrum current of phase b

Figure 10. Harmonic spectrum current of phase c

5.   CONCLUSION

In order to improve the power quality performance in term of lower total harmonic distortion (THD) and reduce the power ripple, this paper propose a control method, namely the predictive direct power control (PDPC) for grid-connected dual-active bridge multilevel inverter (DABMI). DABMI enable the generation of 64 feasible switching states with 37 unique voltage vectors. Modulation stage is unnecessary with on-line optimisation is perfomed through minimizing a cost-function to obtain the optimized voltage vector for each sampling period. By directly controlling the active power P and reactive power Q, grid current is automatically aligned with the grid voltage without the need of additional synchronization module such as phase-locked-loop (PLL). It is found that the proposed control method managed to produce low power ripple and achieve low current THD which is well within the IEEE standard.

REFERENCES

[1] Thangaraj, K., et al, "Power Quality Analysis and Enhancement of Grid Connected Solar Energy System," *Circuits and Systems*, 2016. 7(08): p. 1954.
[2] Singh, A., et al, "Power quality issues related to distributed energy source integration to utility grids," *India Conference (INDICON)*, 2010 Annual IEEE. 2010.
[3] Aurtenechea, S., et al. Predictive direct power control-a new control strategy for dc/ac converters. *IEEE Industrial Electronics, IECON 2006-32nd Annual Conference*, 2006.
[4] Ahmad, S., et al. "Grid connected multilevel inverters for PV application," *Energy Conversion (CENCON), 2015 IEEE Conference*, 2015.
[5] Chowdhury, S., et al, "A dual inverter for an open end winding induction motor drive without an isolation transformer," *Applied Power Electronics Conference and Exposition (APEC), IEEE*. 2015.
[6] Meinguet, F., et al., "Fault-tolerant operation of an open-end winding five-phase PMSM drive with inverter faults," *Industrial Electronics Society, IECON 2013-39th Annual Conference of the IEEE*. 2013.
[7] Chowdhury, S., et al., "A Multilevel Converter With a Floating Bridge for Open-End Winding Motor Drive Applications," *IEEE Transactions on Industrial Electronics*, 63(9): p. 5366-5375,2016.
[8] Casadei, D., et al. "Switching technique for dual-two level inverter supplied by two separate sources," *Applied Power Electronics Conference, APEC 2007-Twenty Second Annual IEEE*, 2007.
[9] Corzine, K., S. Sudhoff, and C. Whitcomb, "Performance characteristics of a cascaded two-level converter," *IEEE Transactions on Energy Conversion*, 14(3): p. 433-439,1999
[10] Masisi, L., et al., "A comparison between 2-level and 3-level inverter for A permanent magnet synchronous motor drive under different inverter switching frequencies," *Power Electronics, Drives and Energy Systems (PEDES), 2012 IEEE International Conference*, 2012.

[11] Brychcín, J., et al., "Modulator for 4-level Flying Capacitor Converter with Balancing Control in the Closed Loop," *Transactions on Electrical Engineering*, p. 66, 2016.

[12] Patnaik, S.S., et al., "Three-level H-bridge and three H-bridges-based three-phase four-wire shunt active power filter topologies for high voltage applications," *International Journal of Electrical Power & Energy Systems*, 51: p. 298-306, 2013.

[13] Taha, O.A., et al., "Hardware implementation of balance control for three-phase grid connection 5-level Cascaded H-Bridge converter using DSP," *Industrial Electronics (ISIE), 2014 IEEE 23rd International Symposium,* 2014.

[14] Janik, D., et al., "Universal precharging method for dc-link and flying capacitors of four-level flying capacitor converter," *Industrial Electronics Society, IECON 2013-39th Annual Conference of the IEEE*. 2013.

[15] Pouresmaeil, E., et al., "Control scheme of three-level NPC inverter for integration of renewable energy resources into AC grid," *IEEE systems journal*, 6(2): p. 242-253, 2012

[16] Lee, S.S., "Optimal VF-PDPC of grid connected inverter under unbalanced and distorted grid voltages," Electric Power Systems Research 140 (2016): 1-8.

[17] Zhong Q. C., et al., "Self-Synchronized Synchronverters: Inverters Without a Dedicated Synchronization Unit," in *IEEE Transactions on Power Electronics*, vol. 29, no. 2, pp. 617-630, Feb. 2014.

[18] Lee, S.S., et al., "Predictive direct power control of multilevel direct current link converter for grid connected battery energy storage systems," Journal of Renewable and Sustainable Energy 8.3 (2016): 034104.

BIBLIOGRAPHY OF AUTHORS

Hui Hwang Goh received B. Eng, M.Eng and PhD. degrees in Electrical Engineering from Universiti Teknologi Malaysia in 1998, 2003 and 2007 respectively. He is currently an Associate Professor with the Department of Electrical Power Engineering, Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja, Malaysia. His research interests include embedded power generation modeling and simulation, power quality studies, wavelet analysis, multicriteria decision making, renewable energies, and dynamic equivalent. Dr. Goh is a member of the Institution of Engineering and Technology, U.K. He is also a member of the Institution of Engineers, Malaysia (IEM), a Chartered Engineer under the Engineering Council United Kingdom (ECUK), and a Professional Engineer under the Board of Engineers, Malaysia (BEM).

Azuwien Aida Bohari was born in Batu Pahat, Johor in the year 1987. She was awarded B. Eng (Hons.) and M. Eng in Electrical in 2011 and 2016 from Universiti Tun Hussein Onn Malaysia. She is currently a PhD. student in the faculty of Electrical and Electronic Engineering, Tun Hussein Onn University, Malaysia. Her research interest include power electronics, control strategies for drive system and renewable energy integration.

Sze Sing Lee received the B.Eng. (Hons.) and PhD. degrees in electrical engineering from the University of Science Malaysia, Penang, Malaysia, in 2010 and 2013, respectively. He is currently an Assistant Professor at the University of Southampton Malaysia Campus, Johor Bahru, Malaysia. His research interests include alternative power converter topologies and control strategies for renewable energy integration.

Sy Yi Sim received B.Eng. (Hons.) and PhD. degrees in Electrical engineering from Universiti Tun Hussein Onn Malaysia, in 2012 and 2016, respectively. She is currently a Lecturer with the Department of Electrical Engineering Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia. Her current research interests include the area of power electronics, motor drives control, renewable energy integration and artificial intelligence control.

Kai Chen Goh received B. Sc (2005) and M. Sc (2006) from Universiti Teknologi Malaysia and PhD. (2011) in Built Environment and Engineering Queensland University of Technology. He is currently an Associate Professor with Department of Construction Management, Faculty of Technology Management and Business, Universiti Tun Hussein Onn Malaysia, Parit Raja, Batu Pahat, Malaysia.