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太陽光發電技術之研究與新型太陽光變頻器之研製(II)

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能源科技學術合作研究計畫成果報告

太陽光發電技術之研究與新型太陽光變頻器之研製 (2/3)

計畫編號：NSC 93－2623－7－009－012－ET
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計畫主持人：鄒應嶼 教授
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本成果報告包括以下應繳交之附件：
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執行單位：交通大學電機與控制工程系

中 華 民 國 94 年 1 月 30 日

目　　錄

摘　要

應用太陽能於再生能源發電系統，由於具有環保易於安裝等優點，再加上商品化技術的成熟與國家計畫性的輔助推動，已成為先進國家發展分散式電源系統的主要選擇。太陽能光伏變頻器 (photovoltaic inverter, PV-inverter)可直接將太陽能光電池所產生的電能饋入市電，因此不僅可提供使用者的自用電源，也可提供公眾電源另一種型式的電力來源，形成一個分散式的發電系統。由於光伏變頻器具有廣大的市場發展潛力，先進國家已開始制訂法規來規範併聯電系統的產業安全標準。有鑑於光伏變頻器未來的發展潛力，本計畫發展高性能在線型太陽光發電系統的關鍵技術，並製作一個模組式併網型多功能太陽光發電系統。本計畫為期三年，研究與發展高效率光伏變頻器的系統設計與控制技術。第一年著重於高效率光伏變頻器的功率級設計，第二年著重於併網控制技術發展，主要包含數位式低諧波失真電流控制技術與最大功率追蹤控制技術之發展與實現，本階段完成一個以單晶片DSP為控制核心的110V、60Hz併網型光伏變頻器，額定功率為2kW，最高功率轉換效率達94%，額定輸出電流總諧波失真為3.5%，測試性能超越一般商品化之併網型光伏變頻器。

關鍵詞：

太陽能光電池、光伏變頻器、DSP控制、市電併聯控制、最大功率轉換追蹤控制、孤島效應偵測與保護、智慧型最大功率追蹤控制

Abstract

This project focuses on the development of advanced digital control technology for utility-tied photovoltaic inverters. Solar energy has found its great potential in the development of renewable energy due to its easy installation, low cost, and direct applications to the current utility network. The photovoltaic inverter, PV-inverter, can directly transfer the solar energy form the solar cells to the utility power network. The PV inverter can provide electrical power to the home appliances as well as electricity to the utility without using the cumbersome battery. Applications of the PV inverters make it possible to realize distributed power generation systems, this can greatly relief the requirement to build conventional power plants. Because of the great potential in promotion the PV inverters in residential electrical generation, industrialized countries are now proceeding legislations of standards and regulations for utility interface of residential and intermediate PV systems. In order to keep cope with the future development trend, this three-year project focuses on the development of key technologies for advanced utility-connected PV inverters. In the first year, we focused on the development of a high-efficiency modular power converter for the utility-connected PV inverters. The second year focuses on the development of grif-connected current-fed control technique and maximum power tracking for solar power conversion. A DSP-based grid-connected PV inverter has been implemented to verify the proposed control schemes. The designed PV inverter has a rating of 2 kW for 110V, 60 Hz utility. A maximum efficiency of 94% has been achieved with a current THD lower than 3.5%. The measured performances are better than most of commercial PV inverters.

Keywords：solar cell, photovoltaic inverter, utility-tied inverter control, robust control, maximum power point tracking, islanding detection and protection, DSP control, intelligent control

一、計劃緣由與目的

1.1 太陽光發電系統

再生能源(renewable energy)係指可自行再生的能源，例如日光能、風能、潮汐能、地熱能、生物廢料能等等[1]-[4]。將再生能源有效且經濟的轉換為一般民生供電，已成為先進科技國家兼顧環保與發電的重要產業發展政策。此外，根據全世界石油生產統計[5]，石油產量將於十年內達到高峰，爾後產量將逐年降低，這不僅意味著油價(包括電價)將不再便宜，也可能導致真正石油危機的到來，間接引發全球經濟風暴。有鑑於再生能源對未來世界環保與經濟發展的重要性，各先進國家無不全力推動再生能源的發展計畫[6]-[9]。

太陽光變頻器(Photovoltaic inverter, 簡稱PV inverter)可直接將太陽能光電池所產生的電能饋入市電，如圖1.1所示，不僅可提供使用者的自用電源，也可提供公眾電源另一種型式的電力來源，形成一個分散式的發電系統。太陽光發電技術可以說是電力電子技術、發電技術、與光電材料技術的綜合衍生技術，太陽光變頻器是其衍生之關鍵產品。雖然環保與能源危機是引發太陽光變頻器發展的原因，但是其市場發展契機則取決於發電效率與成本等兩大因素。

由於過去三、四十年來持續發展高污染工業，台灣的自然環境已受到嚴重的破壞，台灣溫室效應氣體CO2的排放量，在公元2010年將超過1990年的兩倍，且每年夏季均面臨電力不足的危機，其中夏天尖峰負載用電量遠高於離峰用電量是很重要的原因，導致在每天的用電高峰時刻均有限電的可能，對社會造成巨大損失，因此若能有效抑低尖峰用電量，或以再生能源供給之，則台灣將可擺脫限電的惡夢與減少對自然環境的破壞。

由於全球的氣候改變，以及可預見未來的石化能源危機，太陽光電能因其乾淨的特性與未來巨大的開發潛力，而受到各國政府、公司及民眾的

青睞。特別是在日本及歐洲，太陽光電能系統已風靡工業界。像是利用太陽光電能來提供路燈照明、通訊中繼站、及一些緊急用電的例子不勝枚舉。在貧窮的國家，估計約有十億人住在沒有市電的鄉村，若能利用太陽光電能提供電視、收音機、照明等家用電力，是最符合經濟效益與環保的解決方案。

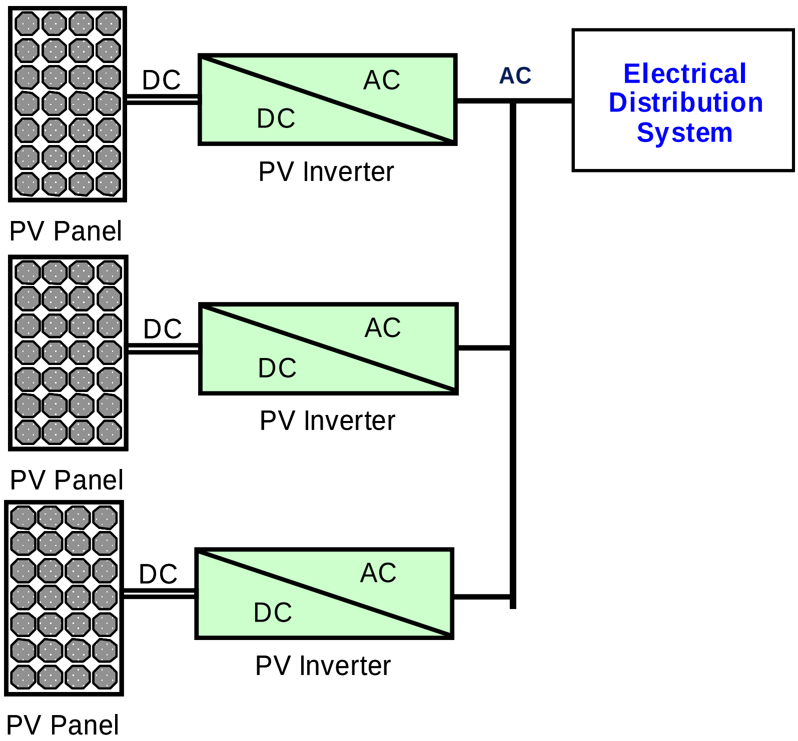


圖 1.1 太陽能發電系統的系統架構圖

自1992年起，美、歐、日等國之電力公司，已展開向住宅用太陽光電能供電系統購買多餘電力(net metering)之行動，以緩和電力公司在尖峰用電時供電不足之窘態。德國與日本政府更以補助方式鼓勵住宅用太陽光電能供電系統之開發與使用，其中日本政府的補助金額更高達全部費用的三分之二。台灣的能源95%以上均仰賴進口，更應極力推廣太陽能的應用，以彌補石化能源之不足。

從長期投資觀點而言，太陽光發電是最符合經濟與環保效益的，恩此歐美先進工業國家，已開始推動住宅用太陽光電能系統。由於目前太陽光發電系統仍然相當昂貴，因此多由政府提供補助優惠措施，來協助系統的安裝及採取有效的方法來推廣太陽光電能系統的使用，更須立法使電力公司來購買系統多餘的太陽光電能，使太陽光電能系統在系統電力的供給上更具彈性及效益。

日本政府於1994年已訂定了完善的住宅用太陽光電能供電系統安裝補助計畫。此計畫不但促使日本頂尖的半導體公司及液晶顯示器公司更積極投入此太陽能市場的生產與製造，更創造了無限商機。日本政府每年約花費11億日元在住宅用太陽光電能供電系統安裝的補助計畫上，它的目標是全日本3%的電力消耗要由太陽能來提供，也就是相當於5 GW的電力。

1997年6月美國能源部提出Million Solar Roofs Initiative (MSRI)草案，期望在2010年在美國建構完成一百萬個具有太陽能能源系統的建築，1998年美國柯林頓政府實施『百萬太陽能屋頂計畫』(million solar roofs program)，有計畫的推動太陽光電能及太陽能熱水器的使用，目前美國約有10,000個太陽能屋頂，預計2010年全美國將有超過一百萬個太陽能屋頂。

歐聯的能源委員會也提出一計畫在歐洲補助建造500,000棟的太陽能房屋，並在開發中國家另建500,000棟太陽能房屋，歐洲政府每年花5億美金來補助此計畫。在歐洲荷蘭的Nieuwland計畫，建立一了座太陽能社區，它包含有5,000個房屋且擁有、公寓、綜合運動場、育護中心及學校各一座，而所有的建築全部裝有太陽光電板，可發約1 MW的太陽光電能。此電力不僅夠社區消耗，而且剩餘電力更可完全饋回市電。此Nieuwland計畫只是冰山一角，指示著太陽能時代的來臨。全世界太陽光電能系統自1990年後，正以驚人的速度成長，其總發電量為30 MW。而1997年首次超過100 MW大關，從90 MW向120 MW趨進。直至1998年年底，全球太陽光電能總發電量已達750 MW。

太陽能產業正持續成長，為將來的地球能源展露了一道曙光。它不僅有20%的年成長率，而且價格也在下降中。它的應用領域也不斷擴增，效率更加提昇，使用壽命長達20年以上。然而太陽光電能供電系統有不易取得、不易與市電整合、不易量測系統發電量等問題，並且價格昂貴。為了解決此問題及增加太陽光電能系統的親和性，必須從減少系統元件數目、降低系統售價及提高系統效能著手。為達此目的，選擇適當的太陽光電板及合適的太陽光電能系統是兩大關鍵。

1.2 PV inverter市場發展趨勢

就太陽光發電系統而言，併聯型 PV inverter 將最具發展潛力，原因如下：

1. 從實際的併聯系統得到的經驗可推廣至許多相關應用上。
2. 併聯系統將使政府在“能源自主”及“無污染能源開發”的投資上得到回收。
3. 併聯系統可遞送太陽光電能至市電，降低了市電尖峰用電量的需求，並可節省電力公司為了每日僅供應數小時的尖峰用電所增加的發電機組，同時也減少了燃料的消耗及 CO2 的排放。
4. 目前電力的儲存仍需依靠蓄電池，但蓄電池所佔空間龐大，且所費不貲。而併聯系統之不足電力可由市電來提供，省去蓄電池等儲能設備。
5. 併聯系統對於想要安裝太陽光電能系統且有能力負擔的民眾提供選擇。

但是要將此種併聯系統應用在商業大樓上，則因其所有權、付款、及售價等問題大大降低了需求。併聯系統要有廣大的市場就非住宅用系統莫屬了，如圖1.2所示。它不但易於市電整合、易於量測發電量、且價格比較便宜。然而，傳統的系統架構複雜，如圖1.3所示，它通常有直流到直流轉換器做最大功率點追蹤(MPPT)或兼做充電器，再經一級直流到交流換流器產生交流輸出，再與市電併聯供電。傳統系統因多級串接，不但體積龐大、價格昂貴、且效率低落。

為了解決以上的問題，本計畫採用圖1.4的架構來實現併聯系統，省去了一直流到直流轉換器及昂貴的儲能設備。此外，期望以數位信號處理器TMS320F24xx來控制換流器達成最大功率追蹤、併聯運轉(grid-connection mode)及自立運轉(stand-alone mode)的正常動作及實現一些簡單保護功能。如此系統在縮小體積、減輕重量、降低成本上有所突破，也符合目前電子系統中輕、薄、短、小和數位化的趨勢，更提高了系統的實用性及可靠度。

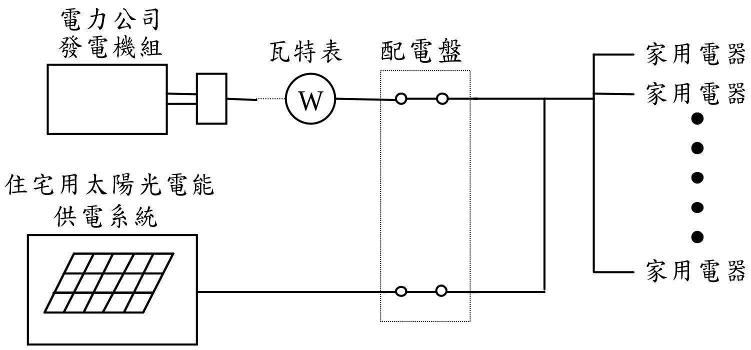


圖 1.2 住宅用太陽光電能供電系統與電力公司連接示意圖

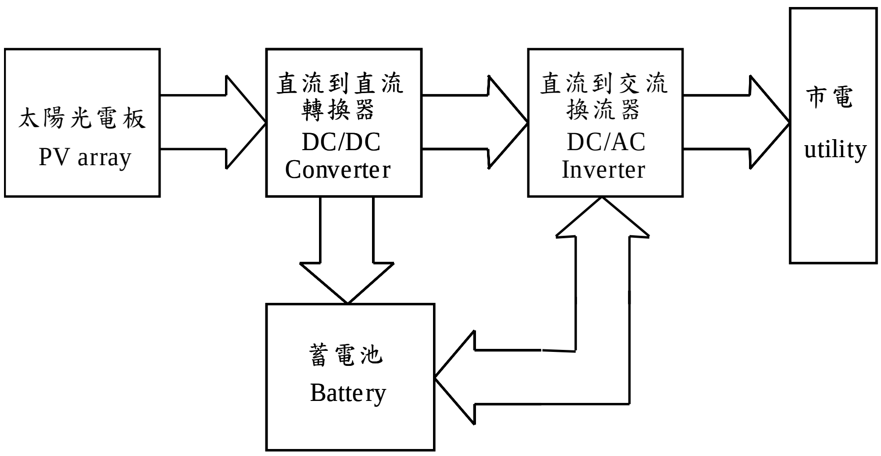


圖 1.3 傳統併聯型太陽光電能供電系統架構圖

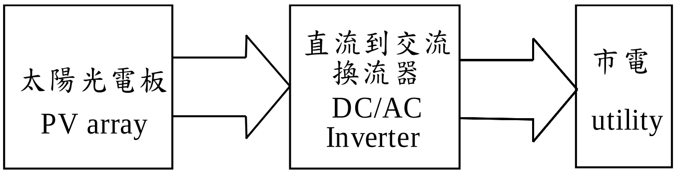


圖 1.4 單級之併聯型太陽光電能供電系統架構圖

併聯型太陽能發電系統的應用雖然可以解決諸多的能源問題，但由於電力的併聯，太陽能發電系統經由市電網路的連結將直接對電力系統及其他各用電戶造成影響。其影響所及除了本身之太陽能發電系統與電力系統之供電設備及其他用電戶之設備外，還包括維修工作人員及公眾的安全以及電力系統的電力品質與供電可靠度等。而隨著趨勢的發展，將會有越來越多的太陽能發電系統併聯於市電網路上，太陽能發電對電力系統的影響也將更趨明顯。因此，併聯系統之保護協調將是不容忽視的重要課題。

併聯系統之保護裝置簡稱為連結系保護裝置，其設置具有局限化故障事故範圍之意義。在併聯系統中，當太陽能發電系統發生故障時，為避免波及併聯系統，太陽能發電設備應即時與電力系統解除併聯；而當所併聯之電力系統發生故障時，亦須要將太陽能發電設備迅速且確實地與電力系統解除併聯，其目的除了確保太陽能發電系統不因電力系統之故障事故而發生損毀外，亦保證包含一般用戶之部分系統不發生單獨運轉之情形，亦稱之為孤島效應 (islanding phenomenon)。

所謂的單獨運轉是指用戶自備發電設備併聯之電力系統與其系統電源切離，而僅由用戶自備發電設備群來發電並對線路負載供應電力之狀態。在太陽能發電系統與市電併聯運轉的狀態下，如因輸配電線事故等使系統電源被中斷時，若不立刻將太陽能發電系統予以切離的話，將發生安全上的問題以及再送電時出現障礙等。

太陽光發電系統是一個包含多種關鍵元件與技術的綜合產品，一般的太陽光發電系統包含太陽光模組、變頻器、與電池。太陽光模組與電池技

術的發展，主要在於材料技術，不是本產品開發計畫的重點。太陽光變頻器基本上是一個以電力電子技術為核心的電源轉換產器，其性能評估指標包含多項因素，如效率、功率密度、輸出電流總諧波失真、功率變化穩定性、最大功率轉換追蹤控制之整體效率、可靠性、每瓦價格、控制技術、安全保護等等。工業先進國家在太陽光變頻器領域的研究發展已有相當時日，這其中的關鍵技術包括：最大功率轉換追蹤控制、電網併聯控制、孤島效應偵測與控制、認證標準與安全規範製定等等，國內近年來也致力於太陽光發電技術的發展，但在產品開發方面，仍有相當的距離。本計畫發展發展併聯型太陽變頻器的關鍵技術，建立提升國內產業界發展新型併聯型太陽變頻器的基礎。

1.3 報告內容

本報告共分九章，內容安排如下：第一章說明計劃緣由與目的，同時說明目前太陽光發電系統的發展現況與趨勢。第二章探討併網型太陽光變頻器的電路架構；第三章針對擬設計的併網型太陽光變頻器提出系統規劃設計與說明；第四章探討DC-DC全橋式轉換器之原理，包括工作模式與轉換器電路設計，接著推導其電路模型並據以設計其電壓模式控制器，其次說明太陽能電池之特性及所採用之最大功率點追蹤控制方法，最後再將所提之最大功率點追蹤控制器與DC-DC轉換器之PV電壓控制結合，由一些PSIM模擬結果來加以驗證所提電路及控制方法之有效性。

第五章說明最太陽光模組最大功率操作點追蹤控制方法的研究現況與本研究所提出的整合型最大功率操作點追蹤控制方法；第六章探討變流器之原理與設計，首先說明採用單電壓極性切換(unipolar voltage switching)之單相電壓源全橋式變流器之原理，接著推導其電路模型，據以設計其各式控制器包括電流迴路以及直流鏈電壓迴路之控制器等。這些控制器之設計並以實際DSP程式撰寫為考量，因此包含了數位控制方式以及C++程式之說

明。最後並將設計所得以PSIM模擬來加以驗證，除包含變流器本身之模擬外，亦結合了DC-DC轉換器作整個系統之模擬。

第七章說明太陽光變頻器的數位控制器設計與實現，並說明併網數位式電流控制之原理與模擬；第八章說明太陽光變頻器之硬體設計與實現；第九章說明本計畫現階段的研究成果與討論。

二、電路架構分析

應用太陽能於再生能源發電系統，由於具有環保易於安裝等優點，再加上商品化技術的成熟與國家計畫性的輔助推動，已成為先進國家發展分散式電源系統的主要選擇。

併網型太陽能光伏變頻器 (photovoltaic inverter, PV-inverter)可直接將太陽能光電池所產生的電能饋入市電，不需要額外的電池組來儲能，如圖2.1所示，因此大幅的降低了電池的安裝與維護成本，也去除了潛在的報廢電池所可能造成的環境污染。

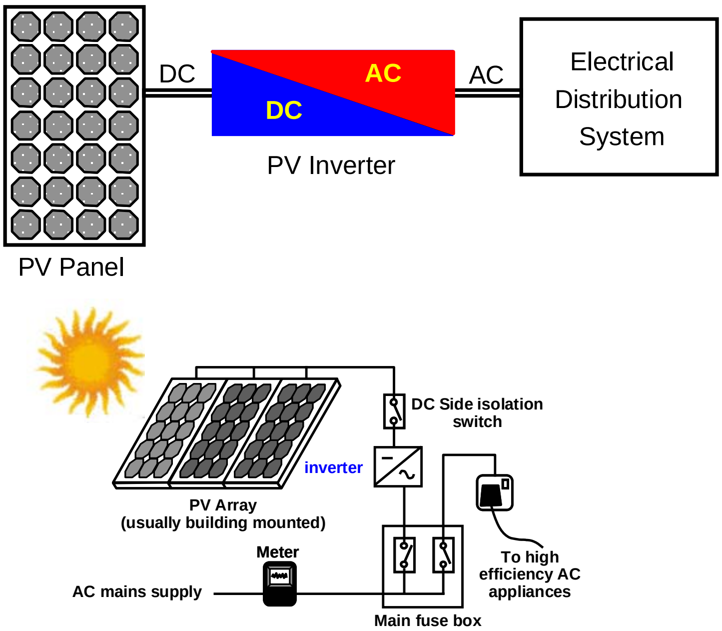


圖 2.1 併網型太陽光變頻器的系統方塊圖

太陽光變頻器根據其應用需求有許多不同的型式，圖2.2所示為不同型式太陽光變頻器的系統架構圖，圖2.2(a)為獨立型太陽光變頻器，將太陽能轉換為負載所需的電能，如獨立使用的電子系統，其供電隨著日照而改變，供電狀況不穩定，一般應用於非關鍵性的場合。圖2.2(b)為可由市電一起供電的混和式太陽光變頻器，負載電能由太陽能與市電提供，負載所需

功率的差額由市電提供，此種型式的變頻器可提供穩定的電源，但若負載所需的電力較低時，亦無法運用所產生的多餘電能。圖2.2(c)為併網型太陽光變頻器，可將太陽光轉換之電能直接饋入市電，系統不需要蓄電池。圖2.2(d)為可提供備份電力的不斷電併網型太陽光變頻器，除了可將太陽光轉換之電能饋入市電以外，當市電中斷時，亦可由電池提供電力並維持系統電力的正常供應。

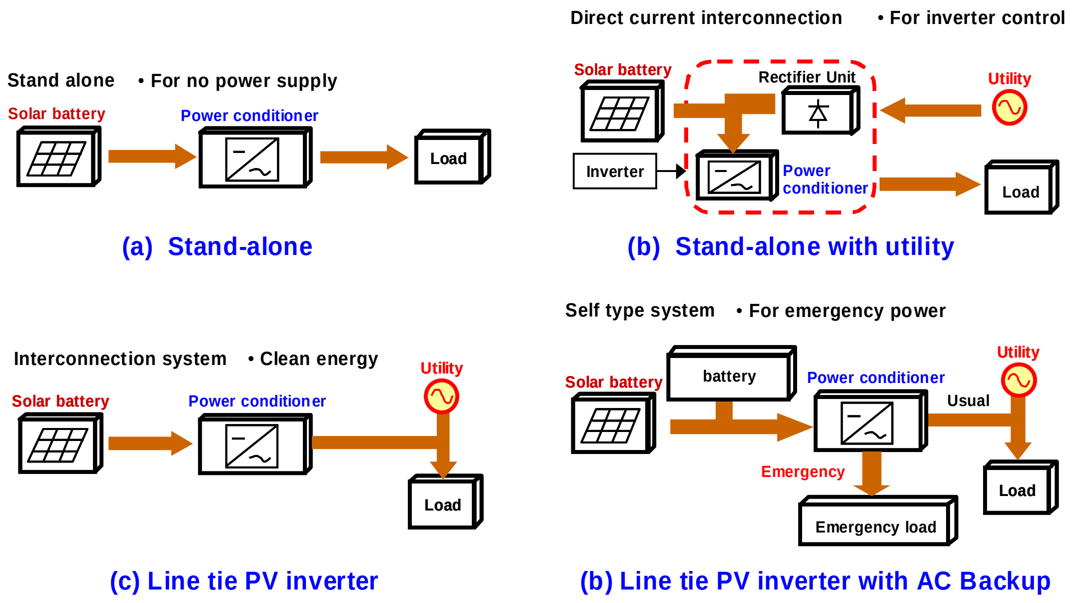
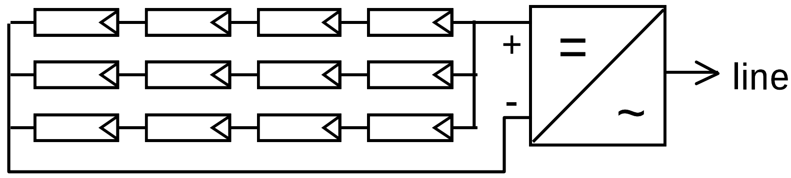


圖 2.2 不同型式太陽光變頻器的系統架構圖

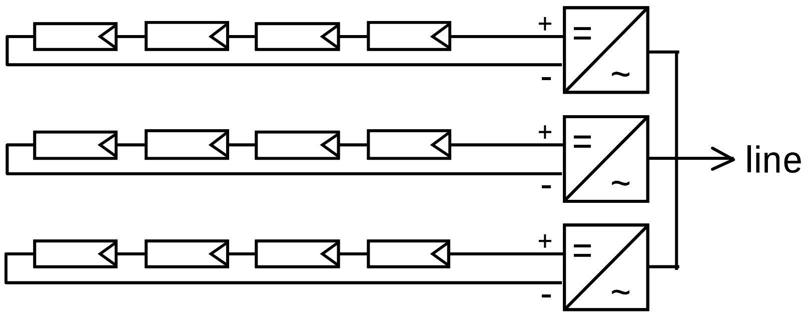
併網型太陽光發電系統由於裝置容量的不同發展出不同架構的太陽光變頻器電路架構如圖2.3所示。圖2.3(a)為集中式的太陽光變頻器，主要應用於大型三相為主的太陽光發電系統。圖2.3(b)為中容量的串聯併網型太陽光變頻器，將太陽能電板模組予以串聯以便獲得較高的電壓，變頻器採用單級式變頻器以提高發電效率。圖2.3(c)為小容量的併網型太陽光變頻器，由於太陽光模組的輸出電壓較低，多採用兩級式變頻器。

由於太陽能電板之發電電壓通常每個約12V左右，不容易達到高壓需求，一般皆須以兩級研製；前級為直流轉換級負責將太陽能板電壓提高，常用者以推挽式直流轉換器予以昇壓，其屬隔離型直流轉換器，但多開

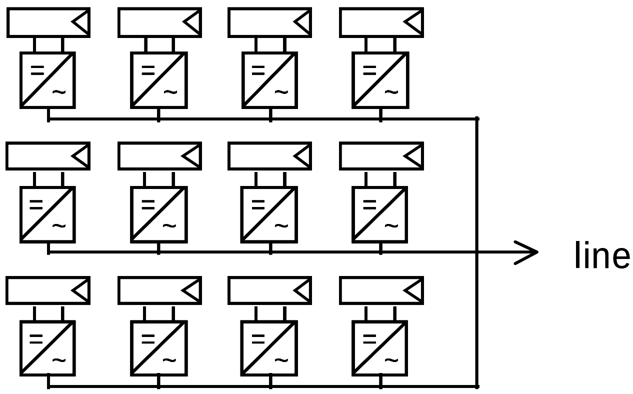
關、體積大為其缺點，影響效率，而效率是太陽光發電系統關性的指標，故尋求單開關、高效率及穩健之直流轉換器及探討成為重要的議題；後級則扮演直流轉交流的變流器角色，目前皆採單相單電壓AC110V或AC220V輸出。



(a) PV plant with central inverter.



(b) PV plant with string inverters.



(c) PV plant with module inverters.

圖 2.3 併網型太陽光變頻器的系統架構圖

併網型太陽光發電系統的架構主要決定於效率與成本因素，系統架構選擇的考量可參考圖2.4。大型的太陽光發電系統為了提高整體效率，通常

採用高壓高流三相的單級式轉換架構，因此其太陽光模組的排列方式必須產生一個高壓高流的直流輸出，反之，小型太陽光發電系統由於太陽光模組低電壓的限制，單板太陽光模組的開路電壓約介於17-22VDC，因此需要以兩級方式，先經由DC-DC升壓器將低壓直流予以升壓，再經由DC-AC變流器，將直流轉換為交流輸出。

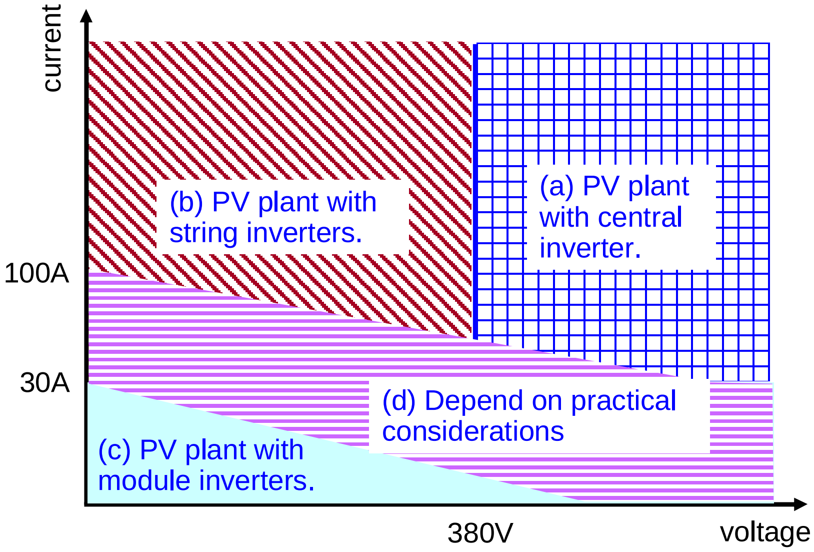


圖 2.4 併網型太陽光發電系統的系統架構選擇的考量

電路架構的分類

設計一個高效能的太陽光變頻器，電路拓撲的選擇，扮演著非常重要的角色，因為電路拓撲主要關係著效率與成本，同時也可能涉及專利導致商業訴訟。

併網型太陽光變頻器的電路架構基本上根據其是否與市電隔離，可分為隔離型與非隔離型，而隔離的方式又可分為低頻(市電頻率)與高頻(一般高於20 kHz)兩種。

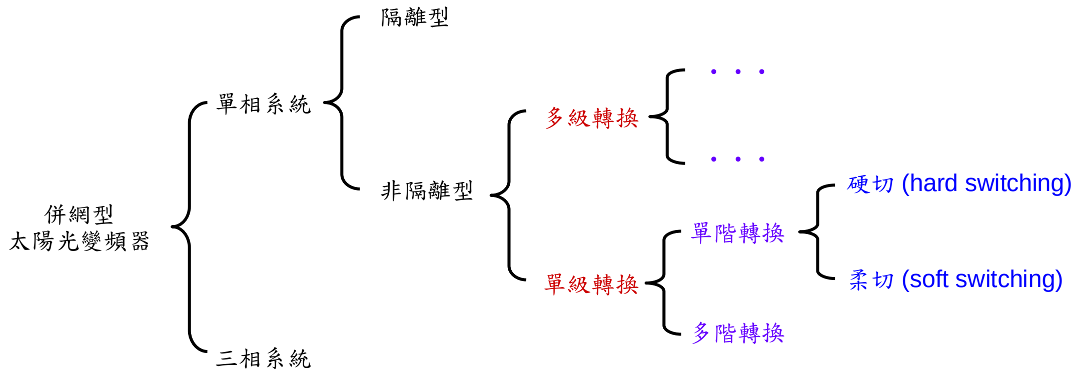


圖 2.5 併網型太陽光變頻電路架構的分類

太陽光變頻器的電路架構基本上是一個採用輸出電流控制的直流轉換成交流的變流器(inverter)，圖2.5是併網型太陽光變頻電路架構的分類，根據輸出的電源相數可分為單相與三相，若根據輸出電流的波形，則可分為方波式、弦波、以及堆疊近似弦波等；根據轉換級數，可分為單級式與雙級式；根據轉換電壓階數，可分為二階式、三階式與多階式；根據開關切換的方式，則可分為硬切(hard switching)與柔切(soft switching)等型式[3]-[12]。早期的(1985-1995)太陽光變頻器多採用雙級式架構，近年來(1996-2004)新型的太陽光變頻器多採用單雙級式架構再配合柔切電路以提高系統的效率。

由於太陽光模組所產生的電壓為直流電壓，一塊單片的太陽光模組(面積約為60cm x 120cm)的最大輸出功率電壓約為17V，因此必須藉由數塊太陽光模組才能得到所需求的功率，同時這些太陽光模組又必須經由適當的串聯與併聯才能得到與太陽光變頻器匹配的輸入電壓與電流。太陽光變頻器的設計為了適應不同太陽光模組的組合同時達到最大功率轉換的效果，其可達到的MPPT輸入電壓控制範圍就成為重要的性能指標。

併網型太陽光變頻器必需要將輸入直流電壓予以升壓及變流(直流-交流轉換)，其電路架構又可分為單級式(single-stage power conversion)與雙級式(double-stage power conversion)。一般而言，單級式的功率轉換效率較高，

但MPPT輸入電壓控制範圍較小；雙級式的功率轉換效率較低，但MPPT輸入電壓控制範圍較大。

圖2.6為變壓器隔離型太陽光變頻器，可藉由變壓器調整電壓轉換範圍，因此可適用於寬廣的太陽光模組輸出電壓範圍，圖2.6(a)為低頻隔離型，優點是可採用低開關頻率、效率高，缺點是低頻輸出變壓器體積較大，輸出功率受限於輸出變壓器。圖2.6(b)為高頻隔離型，優點是體積較小，輸出級為電流饋入變流器，採用市電開關頻率界已降低損失，輸出功率因數大約0.9。

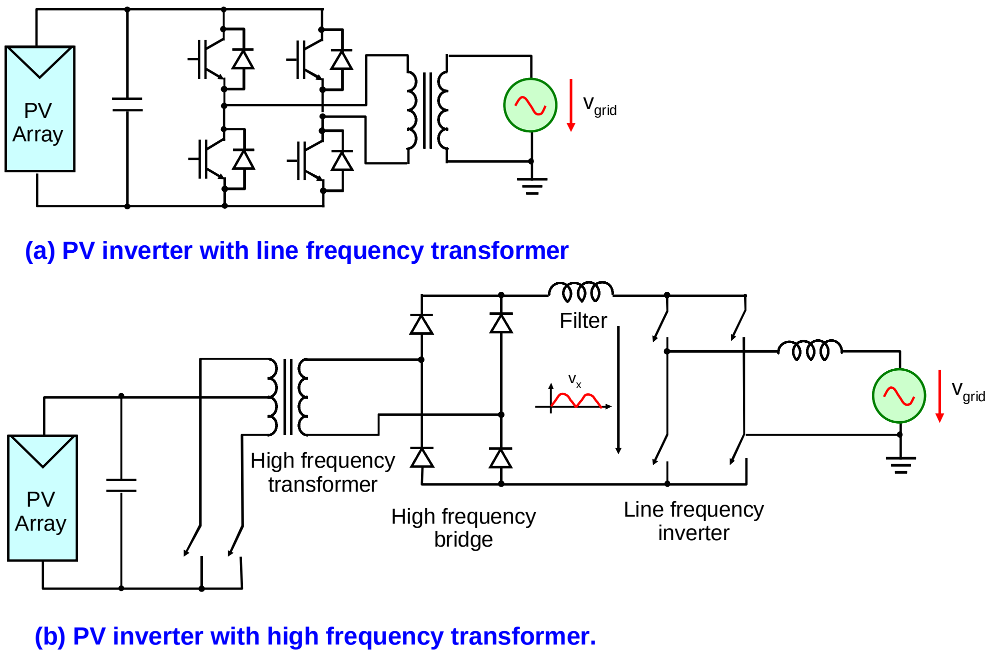
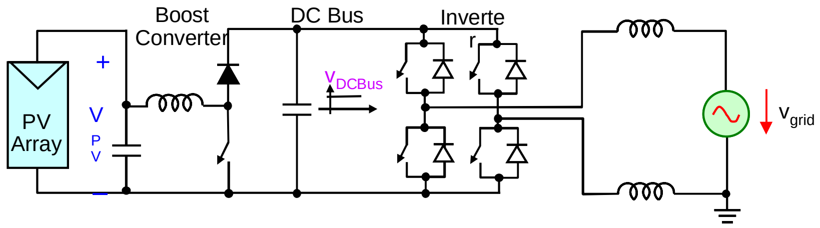


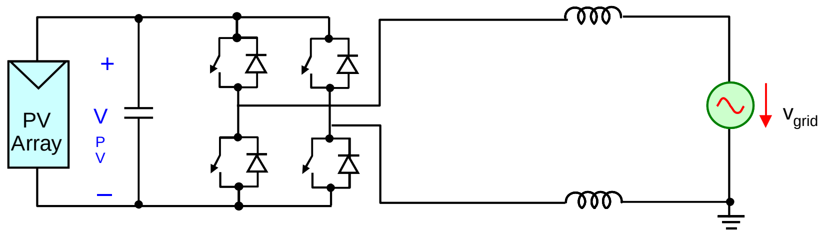
圖 2.6 變壓器隔離併網型太陽光變頻器的電路架構

為了消除低頻變壓器的缺點，近年來併網型太陽光變頻器朝向無變壓器的非隔離型電路架構發展，圖2.7為無變壓器非隔離型太陽光變頻器。圖2.7(a)為兩級式非隔離型架構，前級為升壓型直流-直流轉換器，後級是一個全橋式DC-AC轉換器，直流鏈電壓約為輸出電壓RMS值的兩倍。圖2.7(b)為單級式非隔離型架構，其輸入電壓即為PV array的輸出電壓，因此太陽光模組必須串連產生足夠的直流鏈電壓，由於僅有單級轉換，因此可得到較

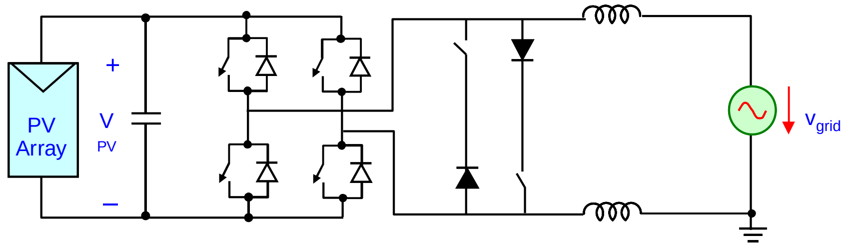
高的轉換效率。圖2.7(c)的輸出級包含了兩個反向的開關，其作用在於提供一個零電壓輸出(電流回流)的機制，用以降低輸出電流漣波，因此可以較低的主開關頻率達到輸出電流低總諧波失真的要求。



(a) Transformerless two-stage PV inverter



(b) Transformerless single-stage PV inverter



(c) Transformerless single-stage PV inverter with bi-directional switches

圖 2.7 無變壓器非隔離併網型太陽光變頻器的電路架構

雙級式單相三線太陽光變頻器

台灣的家庭市電供電線制為單相三線制(1φ3W 110/220V)，光伏變頻器AC220V輸出時無法提供中性點，除非裝設變壓器解決，否則併聯市電時，可能造成兩單相負載不平均而導致分壓不均，致使負載燒毀發生危險事故，因此必須發展單相三線制變流輸出之設計，一般設計以三相六開關形成單相三線輸出，但開關過多不僅降低效率，控制也更為複雜，目前仍處於研究階段，未見商品化之產品發表。

圖2.8所示為本研究提出的新型三線單相式多功能併網型太陽光變頻器的電路架構圖，前級為單開關升壓式直流轉換器，具有電路簡單及效率高之特性，因應太陽能電池在不同日照條件下之輸出電壓變動範圍，調整責任週期比驅動開關切換，提供穩定之直流鏈電壓，二極體並提供前後級隔離及保護太陽能板；同時，配合最大功率追蹤技術，達到最大的能源轉換效率。

後級採用雙半橋式變流電路架構，輸出兩組共地之反相AC110V電壓，再以電壓差觀念，提供相對AC220V之較高輸出電壓，提供台灣地區家庭用戶所適用之市電供電電源單相三線制(1φ3W 110/220V)，除提供兩種電壓選擇之優點外，更可為將來太陽能系統與家庭用電線制之併聯需求，省去變壓器轉換的金錢及空間浪費。

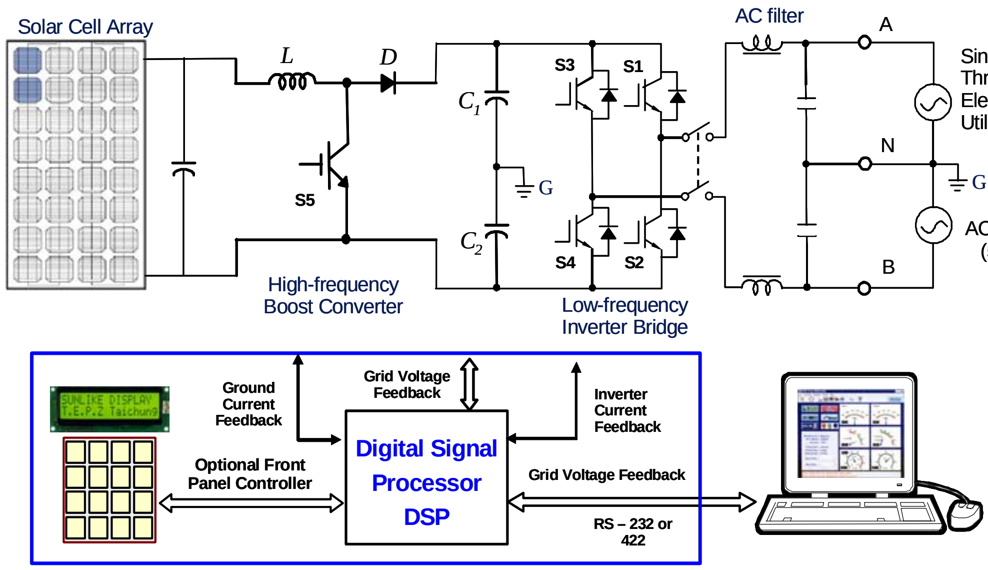


圖 2.8 三線單相式併網型太陽光變頻器的電路架構圖

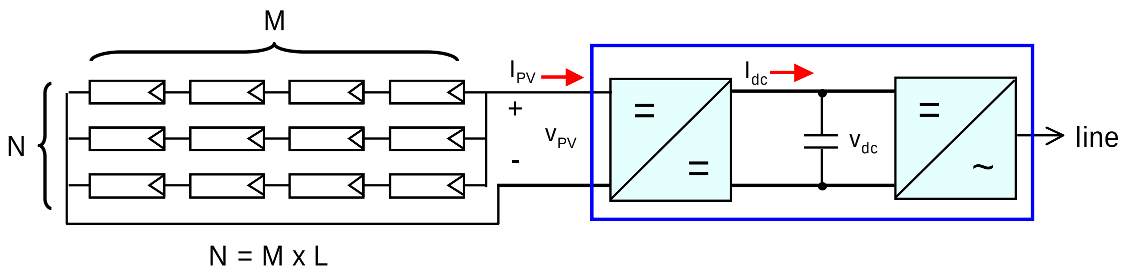


圖 2.9 太陽光模組的排列組合圖

考慮併網型變頻器電路架構的重要考量之一就是效率與成本，電路架構基本上可分為單級式(single-stage power conversion)與雙級式(double-stage power conversion)。雖然單級式電路架構的效率較高，但是直流鏈電壓必須高於市電之峰值電壓，以110V市電而言，直流鏈電壓必須高於150V，考慮實際狀況，一般的直流鏈電壓定於200V，對220V的供電系統，直流鏈電壓則定於400V。雖然雙級式電路架構的效率較低，但可進行最大功率轉換的電壓範圍則較大，整體效率則可能較高，但成本較高。

典型的單板太陽光模組(PV module)為60 cm x 120 cm、100 W、最大功率電壓17V，因此一個併網型太陽光發電系統通常必須要由數十個乃至數百個太陽光模組組成，圖2.9所示是太陽光模組的排列組合圖。決定併網型變頻器電路架構的另一個重要考量之一就是額定功率，一個基本的太陽光模組的額定功率約為100 W，以2 kW併網型變頻器為例，若效率為90%，則輸入功率為2222W，若每塊太陽光模組之最大轉換功率為100W，則需要23塊太陽光模組，為了要組成MxL的矩陣，則需要24塊。24塊太陽光模組有1x24、2x12、3x8、4x6四種組合，其最大輸出功率電壓分別為408V、204V、136V、102V。若考慮110V供電系統，則單級式可採用2x12的組合，對於220V供電系統，則單級式可採用2x12的組合。

現階段由於太陽電池模組的輸出電壓限制，因此低功率(<2 kW)的併網型變頻器多採用雙級式電路架構，但為了降低成本與提昇效率，太陽電池模組的最大功率電壓將逐漸提升，單級式則將成為主流。

分散式電力供應系統

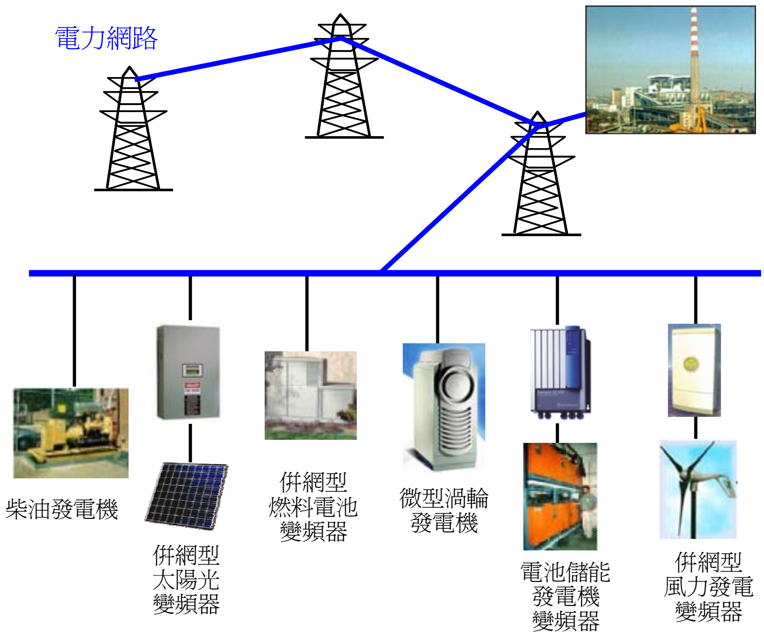


圖 2.10 併網型分散式電力供應系統

併網型太陽能光伏變頻器不僅可提供使用者的自用電源，也可提供公眾電源另一種型式的電力來源，形成一個分散式的發電系統。圖2.10是不同電力來源所形成的併網型分散式電力供應系統，藉由微電子與電力電子技術的發展，二十一世紀將出現眾多這種以小型的分散式電力供應系統，以不同的能量來源來產生電力，這其中併網型變頻器就有如電力網路的控制閘口，具有龐大的發展潛力。

併網型太陽光變頻器的產品分析

太陽光發電系統的商業競爭關鍵主要在於效率與成本。併網型太陽光變頻器的設計考量主要在於效率、可靠度、安全、與成本。

台灣由於地處颱風經常侵襲的地區，因此太陽光模組安裝的安全是首要的考慮因素，應加裝自動防風鎖定系統。

關於太陽光發電的研究，國內外已有相當的發展，由於併網型變頻器具有潛在的廣大應用市場，因此已逐漸成為指標性的規格產品。表1列出目前額定功率約為2kW的商品化併網型太陽光變頻器。調查顯示其功率級已逐漸朝向單級式高壓DC-AC全橋式電路架構發展，太陽光電池模組已以串聯的方式提高其開路電壓，均包含最大功率追蹤控制，MPPT的電壓追蹤控制範圍介於100-400VDC，整機效率約介於92-95%，有些機種也提供網路遠端監控的功能，單位功率價格約為25-30NT/Watt。國內已有包括飛瑞、系統、茂迪等公司進行太陽光發電系統的研發。

表 2.1 商品化併網型太陽光變頻器的比較表

						
Competitor Specifications	**Xantrex STXR2000**	**Sunny Boy 2100TL**	**Omnion 2500 2KW**	**Fronius IG2000**	**Mastervolt QS2000**	**Sysgration Apollo 2000**
AC Output Voltage (Nominal)	240 Vac	240 Vac	120 Vac	240 Vac	230 Vac	110 Vac
AC Output Voltage Range	211~264 Vac	198~260 Vac	105~127Vac	212~264 Vac		104~115 Vac
Continuous Power	2000W	1900W	2000W	1800W	1600W	2000W
Efficency (Peak)	94%	96%	92.50%	94.40%	95%	92%
AC Output Characteristics	Current source					
Frequency (Nominal)	60 Hz	49.8~50.2 Hz	60 Hz	50 Hz	50 Hz	50/60 Hz
DC Input Voltage (Nominal)	48 Vdc	125~600 Vdc	200 Vdc	150~450 Vdc		200 Vdc
Mppt Voltage Range	44~85 Vdc	125~600 Vdc	100~400 Vdc	150~400 Vdc	100~380 Vdc	180~240 Vdc
Full Power Output	52~85 Vdc			450 Vdc	450 Vdc	
Absolute Maximum PV Open Circuit Voltage (Voc)	120 Vdc	600 Vdc	400 Vdc			120 Vdc

三、系統規劃設計

本研究擬發展高性能併網型太陽光發電系統的關鍵技術，並實際製作一個額定功率為2 kW的模組式多功能太陽光發電系統。圖3.1所示是一個併網型太陽光發電系統的系統架構圖，包含四個子系統：太陽光模組、功率轉換器、控制器、與監控軟體。本計畫將發展其中的功率轉換器、控制器、與監控軟體，並整合太陽光模組完成一個額定功率為2 kW的併網型太陽光發電系統。

3.1 系統發展平台

本研究主要著重於併網型太陽光變頻器的數位控制技術，首先針對硬體電路之開路特性分析設計，並以簡化之模型進行多迴路控制器設計，應用不同控制器之特性及優點，達到降低成本、提高能源轉換效率、增加系統頻寬、改善系統暫態及穩態特性之目的。

系統架構之數位控制模擬及控制參數設計採用電路模擬軟體PSIM建構完成，配合自行研發建立之實驗平台，如圖3.1所示，以DSP為基礎之數位控制板、功率級，配合一個自行發展的視窗化DSP監控軟體WinDSP，進行整合實測驗證。經RS-232作為數位控制卡與電腦間資料的連結，因WinDSP具有線上觀察控制波形與調整控制器參數的功能，使控制程式之發展更加方便與快速。

本研究採用PSIM模擬軟體進行數位電源控制模擬及設計，未來將以單晶片DSP實現控制法則做準備，完成全數位控制太陽能光伏變流器整體測試。先由模擬分析確認提出控制架構之可行性，再進行電路與控制的設計與實現。

本研究設計全數位控制之單相三線制太陽能光伏變流器，以數位訊號處理器(DSP)為基礎，全數位式設計達到光伏能之高轉換效率、最大功率追蹤及市電併聯技術及保護等多項複雜之快速控制需求。選擇昇壓型轉換電

路為前級，後級以雙半橋式為輸出之硬體架構，完成一個適用於具有單相三線制系統之地區，提供多電壓之穩定輸出，兼具備用電源提供與高效能環保發電之目的，符合時代需求之趨勢。控制架構前級採用多迴路控制方式，回授調整追蹤太陽能板之最大輸出能量，提供穩定之直流鏈電壓；後級則控制兩組半橋式轉換器輸出提供共地點，適合市電併聯需求以發展併聯技術。

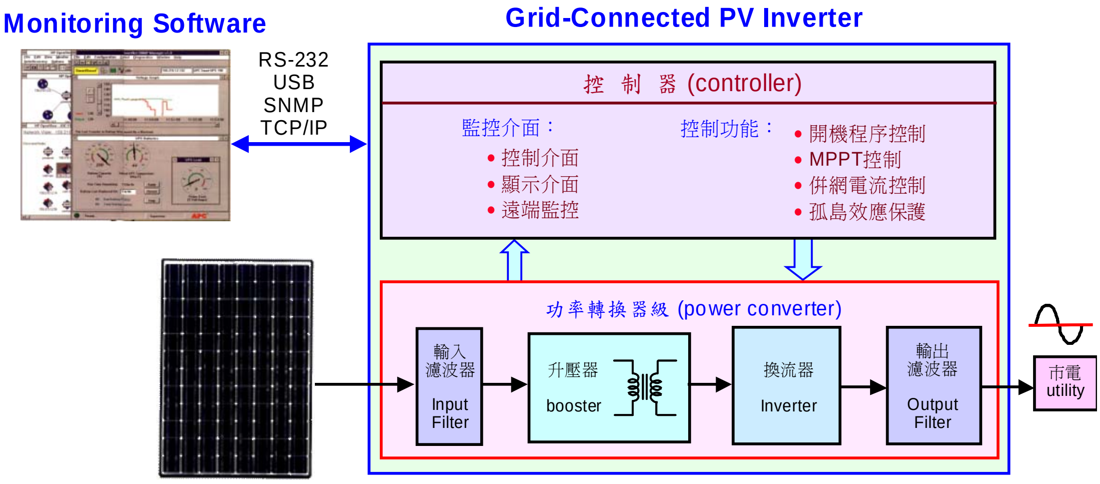


圖 3.1 併網型太陽光發電系統的系統架構圖

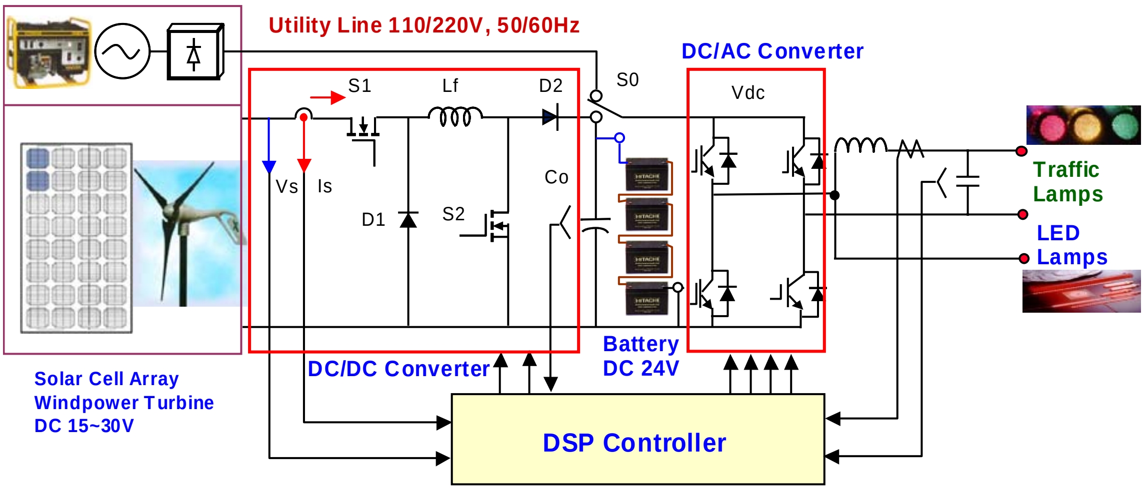


圖 3.2 多功能太陽光變頻器數位控制技術發展平台示意圖

3.2 系統架構及功能

本計畫所研製之太陽能發電系統如圖3.3所示，包含太陽能電池模組(PV modules)、DC-DC轉換器、變流器、同步開關等。電力之轉換為兩級，DC-DC轉換器先將低壓(30~80 VDC)之太陽能電池電壓升壓至200VDC之直流鏈電壓，變流器再將此200VDC之電壓轉換成交流110VAC提供給負載並同時與市電並聯。同步開關(SW)用以在市電異常時將發電系統與市電之連接斷開，以確保太陽能電力不致在市電中斷時仍對市電送電，造成線上可能有維修人員之觸電。太陽能電池模組之容量為2KW，負載最大容量為4KW。DC-DC轉換器及變流器均採用PWM切換，以2KW之轉換容量估算，DC-DC轉換器之效率約為85%，變流器之效率約為90%，因此從太陽能電池端至負載端之電能轉換效率為0.85×0.9=75%左右。

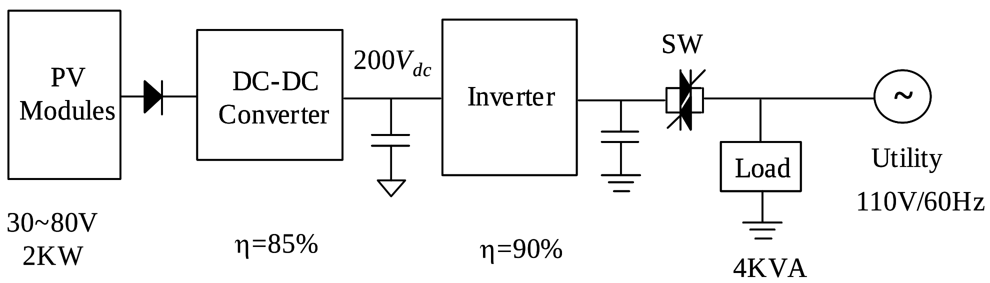


圖 3.3 所研製之雙級式太陽能發電系統架構圖

系統各部分之功能說明如下：

DC-DC 轉換器

由於太陽能電池之電壓會隨著日照強度、溫度及工作點變化連帶影響其功率輸出，因此需借助轉換器控制太陽能電池之電壓(或電流)以得到最高之轉換功率，使太陽能電池之效益達到最高。除此由於變流器所需之直流電壓甚高，因此在太陽能電池容量有限之條件下可能無法直接以太陽能電池串聯得到如此高之電壓，故DC-DC轉換器尚兼具升壓之功能。本計畫將太陽能電池模組電壓設定在30~80VDC之範圍之考量如下：(1)此電壓範圍大

致需要4-5片10~15V之太陽能電池模組串聯，對於使用50W、75W、100W、150W等太陽能電池模組所組成之2KW系統，較易得到適當之太陽能電池陣列組合(分別為4×10、4×8、4×5、5×3)；(2)此電壓範圍與一般電信設備(-48VDC)用途相近，本計畫所開發之轉換器系統及技術等未來亦可以應用至電信設備所需之UPS上。

變流器

變流器之目的為平衡系統之電力，亦即將太陽能之電力轉換至交流側並補充系統本身(包括變流器及DC-DC轉換器)之電力損耗，此平衡電力之控制可以藉由維持直流鏈電壓來達成。此外太陽能藉由變流器饋入市電之電流波形為正弦，在本計畫中設定THD<5%，功率因數>0.995。

同步開關

同步開關之目的在控制太陽能發電系統與市電之連結，當太陽能發電系統與市電均正常且同步時，同步開關導通。反之當太陽能發電系統與市電二者有任一異常或二者未達同步時，同步開關將截止。太陽能發電系統除判斷本身之工作狀況外，亦隨時監控市電電壓，當市電故障時需有能力可以偵測以防止孤島效應發生，同步開關必須適時截止以防太陽能電力繼續饋入系統，造成線上可能維修人員之觸電。

根據太陽能電池之發電量、轉換器、市電等之工作狀況，所提系統可以區分成兩種工作模式：發電模式與停機模式，工作原理說明如下。

發電模式

當太陽能電池模組之電壓在30V~80V範圍內，DC-DC轉換器可以將之升壓轉換至直流鏈。若太陽能所發之電力大於負載之電力需求時，系統之電力潮流如圖3.4(a)所示，太陽能之電力除提供負載使用外，多餘之電力將饋入市電。反之若太陽能所發之電力小於負載之電力之電力需求時，系統

之電力潮流如圖3.4(b)所示，太陽能小於負載電力部分，將由市電自動補充。此模式由於太陽能電池實際發電因此稱之為發電模式。

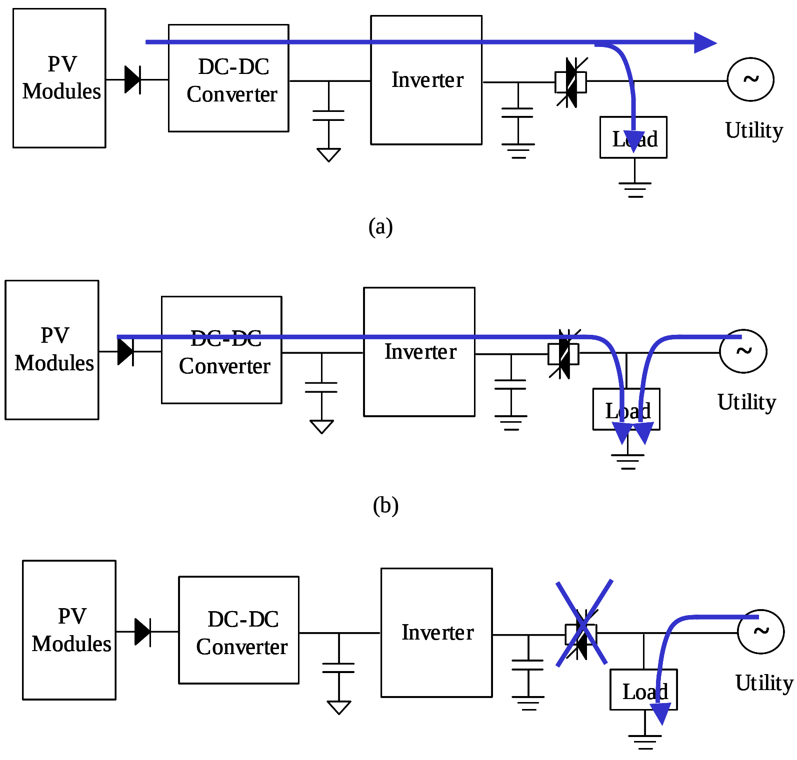


圖 3.4 太陽能發電系統之工作模式：(a) 發電模式(發電量大於負載需求時)；(b) 發電模式(發電量小於負載需求時)；(c)停機模式

停機模式

當太陽能電池模組之電壓在30V~80V之範圍外亦或市電故障時，DC-DC轉換器及變流器都將停止動作，同時同步開關將切離市電，此模式稱之為停機模式如圖3.4(c)所示。在市電正常但太陽能電池模組之電壓在30V~80V之範圍外時仍將整個系統停止之目的為減少系統本身待機之損失。當太陽能電池電壓及市電均恢復正常時，系統內部之同步信號首先與市電同步後再同時觸發同步開關及轉換器，開始發電。

3.3 系統之轉換器電路架構

本計畫所採用之轉換器電路架構如圖3.5所示，其中之DC-DC轉換器採用具變壓器且二次側為全橋形式整流之全橋式轉換器，變流器採用單相電壓源全橋形式；控制器包含MPPT控制器與併網電流控制器，控制器採用單晶片DSP以軟體方式實現。

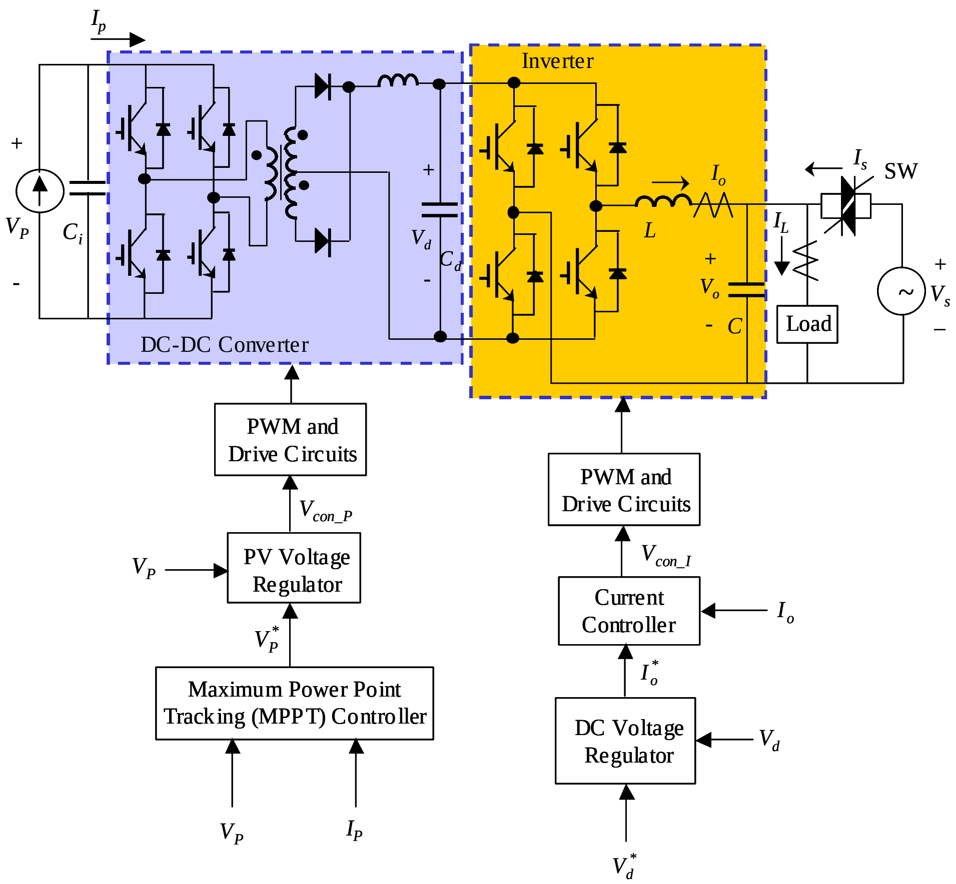


圖 3.5 所採用之轉換器電路架構圖

DC-DC轉換器採用電壓模式控制用以控制太陽能電池之電壓(V_p)，太陽能電池之電壓由最大功率點追蹤(MPPT，Maximum Power Point Tracking)控制器設定，此電壓命令即獲得最大功率點之操作電壓。

DC-DC轉換器之PV電壓調整器將電壓誤差經調整後得到一控制電壓，最後再藉由PWM切換控制得到全橋式開關之觸發信號。在變流器部分則採

用雙迴路控制，外迴路用以調整直流鏈電壓並產生內迴路之電流命令，內迴路則為電流控制迴路使變流器之輸出電流能緊密追隨其命令，電流調整之誤差產生控制電壓，再藉由PWM得到變流器開關之觸發信號。

四、全橋式DC-DC轉換器之原理與設計

4.1 全橋式DC-DC轉換器之原理

如圖3.3所示，所提之雙級式太陽能供電系統利用全橋式DC-DC轉換器以追蹤太陽能電池最大功率點之方式將太陽能轉換至高壓直流鏈側，變流器再以維持直流鏈電壓之方式將太陽能所轉換之電力轉移至交流側。在此以圖4.1之電路來表示全橋式DC-DC轉換器，其中太陽能電池以一電流源、直流鏈電壓則以一直流電壓源來近似實際之狀況。採用PWM切換控制之全橋式DC-DC轉換器之工作波形如圖4.2所示，其中對角線之開關成對觸發(即(Q_1、Q_4)與(Q_2、Q_3))，各負責半週之操作，開關之責任週期由一控制電壓(v_{con})與一週期性之三角波(振幅v_t)比較。分析時假設開關及二極體均為理想，當開關(Q_1、Q_4)觸發導通時($0<t<t_{ON}<T_s/2$)，變壓器一次側電壓為V_p，變壓器之匝數比為n:1，因此二次側之電壓V_2及全橋式二極體整流器之輸出電壓V_{di}均為V_p/n。變壓器匝數比之設定必須使在太陽能電壓為最低時，V_p/n之大小仍大於直流鏈電壓V_d，使電感電壓為正，電感電流I_d在此時為上升，並將太陽能電力轉移給直流鏈。當開關截止時($t_{ON}<t<T_s/2$)，為維持電感電流之連續，二次側四個全橋式整流二極體均導通形成一飛輪使V_{di}電壓

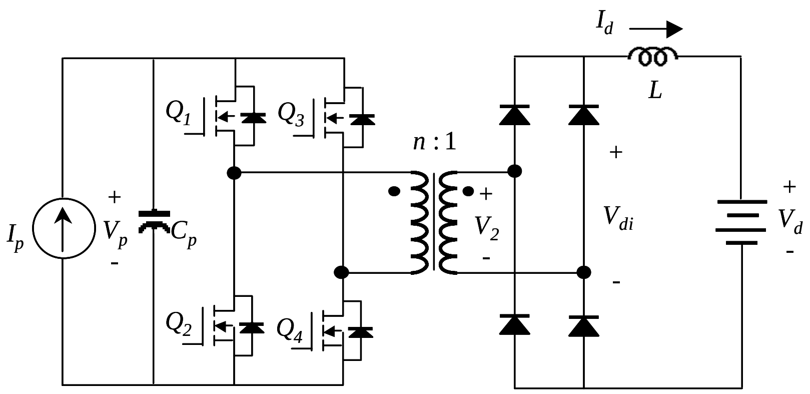


圖 4.1 全橋式 DC-DC 轉換器電路

為零，電感電壓為-V_d，使電感電流下降。後半週動作與前半週類似，但觸

發之開關改為(Q_2、Q_3)，此時 V_2之電壓為-V_p/n 但經全橋式二極體整流後之電壓仍為 V_p/n，電感電流為上升。當開關截止時四個二極體亦形成飛輪使電感電流下降。最後之直流鏈電壓 V_d 為輸入電壓 V_p之平均值，即：

$$V_d = \frac{2t_{ON}}{T_s}\frac{V_p}{n} = \frac{v_{con}}{v_t}\frac{V_p}{n} = D\frac{V_p}{n} \tag{4.1}$$

D 為開關之責任週期。

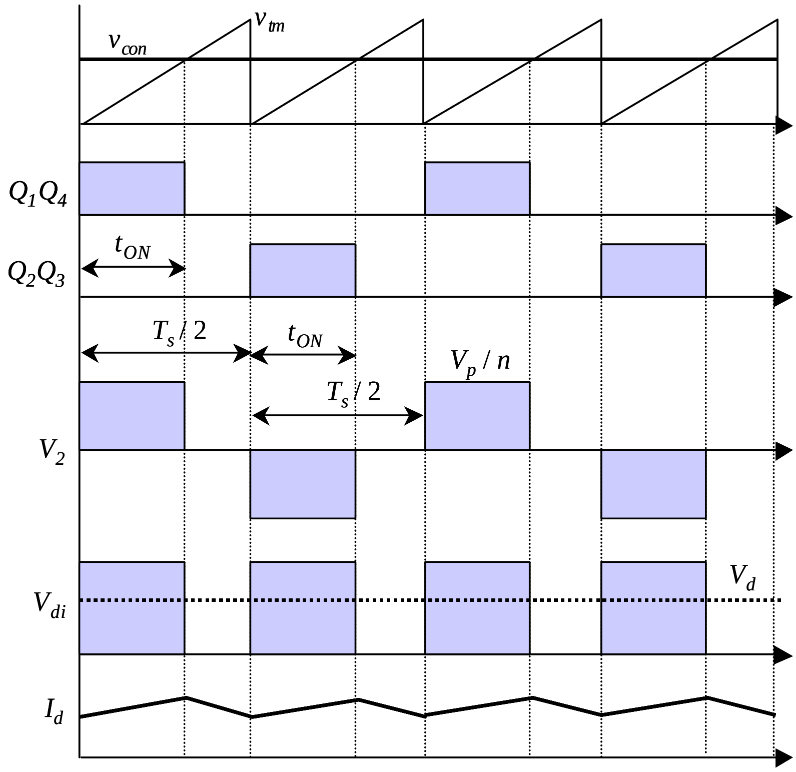


圖 4.2 採用 PWM 切換控制之全橋式 DC-DC 轉換器之工作波形

4.2 全橋式DC-DC轉換器之小信號模型推導

利用狀態平均法由圖4.1之電路可得：

$$C_p\frac{dV_p}{dt} = I_p - D\frac{I_d}{n} \tag{4.1}$$

$$L_d \frac{dI_d}{dt} = \frac{V_p}{n} D - V_d \tag{4.2}$$

在工作點上加一小擾動並移除工作點之穩態值可得電路之小信號模型：

$$C_p \frac{d\tilde{V}_p}{dt} = \tilde{I}_p - D\frac{\tilde{I}_d}{n} - \frac{I_d}{n}\tilde{D} \tag{4.3}$$

$$L_d \frac{d\tilde{I}_d}{dt} = \frac{V_p}{n}\tilde{D} + \frac{D}{n}\tilde{V}_p - \tilde{V}_d = k_{pwm}\tilde{v}_{con} + \frac{D}{n}\tilde{V}_p - \tilde{V}_d \tag{4.4}$$

$$k_{pwm} = \frac{V_p}{nv_t} \tag{4.5}$$

其中"~"表示小信號之變化量。利用(4.3)及(4.4)可得 DC-DC 轉換器閉迴路系統之方塊圖如圖 4.3 所示，其中迴授之信號為輸入電壓 V_p，k_v 為電壓之感測增益。輸入電壓之命令 v_p^* 由最大功率點追蹤控制器產生，G_v 為 PV 電壓控制器。

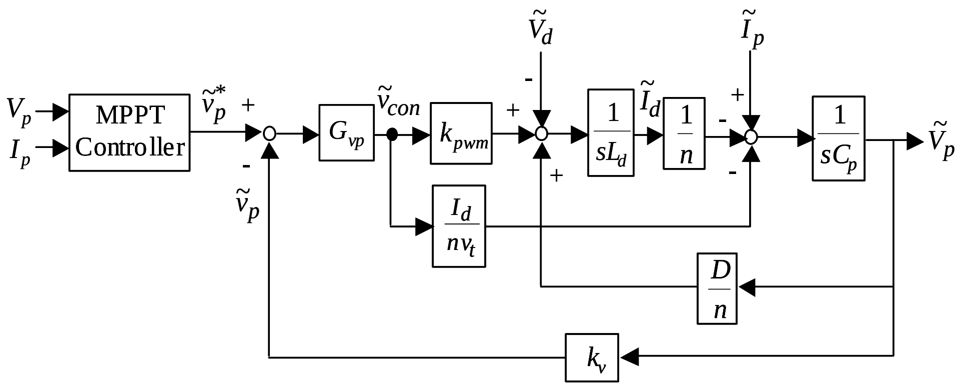


圖 4.3 DC-DC 轉換器閉迴路系統之方塊圖

4.3 全橋式DC-DC轉換器之PV電壓控制器設計

由圖4.3可得電壓控制迴路之轉換器部分開迴路響應為：

$$H_p(s)=\frac{\tilde{v}_p}{\tilde{v}_{con}}=\frac{\frac{I_d k_v}{C_p v_t}(s+\frac{DV_p}{n^2 L_d I_d})}{s^2+\frac{D^2}{n^2 L_d C_p}}=\frac{k_g(s+g)}{s^2+\omega_o^2} \tag{4.6}$$

$$\omega_o=\frac{D}{n}\frac{1}{\sqrt{L_d C_p}},\ g=\frac{DV_p}{n^2 L_d I_d},\ k_g=\frac{I_d k_v}{C_p v_t} \tag{4.7}$$

考慮實際之數值與輸入電壓之變化，$H_p(s)$之波德圖如圖 4.4 所示，其中極點 $g(>>\omega_o)$非常高，設計控制器時予以忽略。共振頻率 w_o及低頻增益$(k_g g/w_o^2)$將隨輸入電壓之變化而變化，輸入電壓越高增益越高但共振頻率越低；反之，輸入電壓越低增益越低但共振頻率越高。控制器可以採用 PI 控制器：

$$G_{vp}=\frac{k_d(s+z)}{s} \tag{4.8}$$

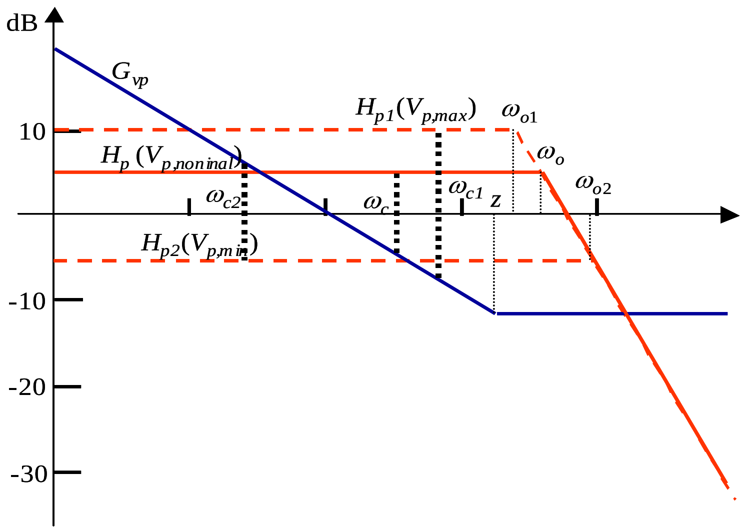


圖 4.4 $H_p(s)$之波德圖以及 PI 控制器之設計

若選定 $z<\omega_{o(\min)}$(即圖中之ω_{o1})，則可滿足系統之迴路增益$(G_{vp}H_p)$在任一輸入電壓下之零交越頻率 ω_c(crossover frequency)時之增益斜率均為-20dB/decade，而且最終之下降斜率均為-40dB/decade，滿足穩定度之要求。由圖 4.4 亦可知，不同之輸入電壓會得到不同之零交越頻率，輸入電壓越

高，零交越頻率越高；輸入電壓越低，零交越頻率則越低。

PI設計之法則為根據一正常(nominal)電壓選定零交越頻率ω_c，再根據$\omega_{o(\min)}$選擇z使z較$\omega_{o(\min)}$稍小，以保證在任何情況下系統均為穩定(即z不大於$\omega_{o(\min)}$)。最後 k_d 之可由下式獲得。

$$\left|G_{vp}(\omega_c)\right| = \frac{1}{\left|H_p(\omega_c)\right|} \tag{4.9}$$

五、全橋式DC-DC轉換器之原理與設計

5.1 太陽能電池特性與最大功率點追蹤(MPPT)控制器設計

太陽能電池特性

太陽能電池模組(PV module)乃由許多太陽能電池(cell)串並聯所組成，每一太陽能電池為由P-N接面的半導體所組成，經由光照射後會形成一電流源提供給負載作功。太陽能電池模組之等效電路如圖5.1所示，其中電流源I_{ph}用來表示太陽能電池模組藉由光照射後所產生之電流，D_j用以表示P-N接面之二極體，R_{sh}和R_s則分別表示材料內部的等效並聯及串聯電阻，在一般情況下，R_{sh}值很大，而R_s值很小，因此一般為了簡化分析起見可將R_{sh}與R_s忽略不計。R_o表示外部負載，I、V則分別表示太陽能電池模組之輸出電流及電壓。

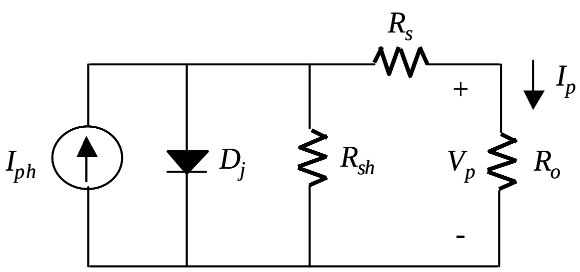


圖 5.1 太陽能電池模組之等效電路

由圖5.1之等效電路，結合半導體P-N接面特性可得太陽能電池模組之輸出電壓與電流方程式：

$$I_p = n_p I_{ph} - n_p I_{sat}[\exp(\frac{q}{kAT}\frac{V_p}{n_s}) - 1] \quad (5.1)$$

其中

I_p：太陽能電池模組之輸出電流(A)

V_p：太陽能電池模組之輸出電壓(V)

N_p：太陽能電池模組之並聯數

N_s：太陽能電池模組之串聯數

q：一個電子之電荷量(1.6×10^{-19} C)

K：波兹曼常數(1.38×10^{-23} J/^{o}K)

T：太陽能電池模組之表面溫度(^{o}K)

A：太陽能電池模組之理想因數(A=1~5)

I_{sat}：太陽能電池模組之反向飽和電流(A)

I_{sat}可以表示如下：

$$I_{sat} = I_{rr}(\frac{T}{T_r})^3 \exp[\frac{qE_{gap}}{kA}(\frac{1}{T_r} - \frac{1}{T})] \tag{5.2}$$

其中

T_r：太陽能電池模組之參考溫度(^{o}K)

I_{rr}：太陽能電池模組在參考溫度T_r時之反向飽和電流。

E_{gap}：半導體材料跨越能間帶間隙時所需能量。

另外，太陽能電池模組所產生之電流I_{ph}將隨日照強度與大氣溫度改變，可用下列方程式近似：

$$I_{ph} = [I_{scr} + \frac{K_i}{1000}(T - T_r)] \cdot S_i \tag{5.3}$$

其中

I_{scr}：太陽能電池模組工作在參考溫度和 1KW/m^2 的日照條件下之短路電流

K_i：太陽能電池模組短路電流之溫度係數(mA/^{o}K)

S_i：太陽的日照強度(KW/m^2)

太陽能電池模組之輸出功率可利用(4.11)求得：

$$P = V_p I_p = n_p I_{ph} V_p - n_p I_{sat} V_p [\exp(\frac{q}{KAT}\frac{V_p}{n_s} - 1] \qquad (5.4)$$

藉由改變日照強度和大氣溫度等條件，由(5.2)、(5.3)及(5.4)可以模擬方式繪出太陽能電池模組之電氣特性圖，包括I_p-V_p以及P-V_p等分別如圖5.2及圖5.3所示。一Siemens製造之75W太陽能電池模組如表5.1所示，圖5.2是模擬此太陽能電池模組在固定環境溫度25^{o}C下當日照度改變時其輸出電流、輸出電壓與輸出功率之關係。可以看出當日照度改變時對太陽能電池之電壓並不會有太大之影響，但對其所能提供的最大電流值有非常顯著之變化，因此日照度強弱勢乃影響太陽能電池模組輸出功率之重要因素。圖4.7模擬此太陽能電池模組在固定日照強度下，當溫度變化時模組輸出電流、輸出電壓及輸出功率之關係圖。由圖可以明顯看出當溫度升高時模組之開路電壓會降低，但其短路電流卻增加，整體而言輸出功率會略為下降，由此可見環境溫度之高低亦會直接影響太陽能電池模組之最大輸出功率。

表 4.1 單一太陽能電池模組之特性(Siemens SP75)

電器特性	規 格
額定最大輸出功率(W)	75
額定電流(A)	4.4
額定電壓(V)	17.0
短路電流 I_{sc} (A)	4.8
開路電壓 V_{oc} (V)	21.7
正常工作電壓 NOTC (^{o}C)	45.2
短路電流溫度係數 K_i (mA/^{o}C)	2.06
開路電壓溫度係數(V/^{o}C)	-0.77

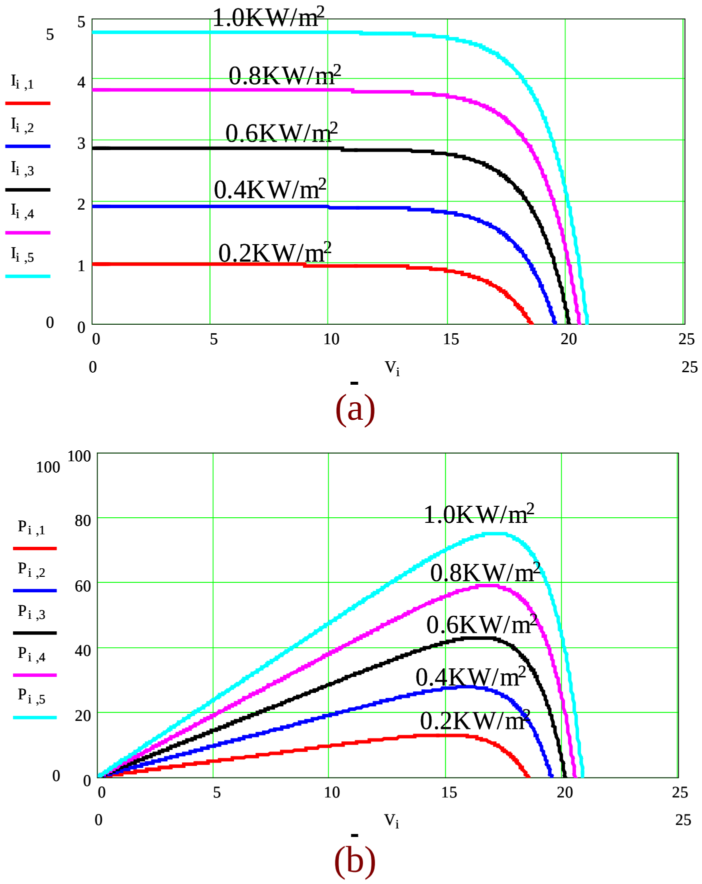
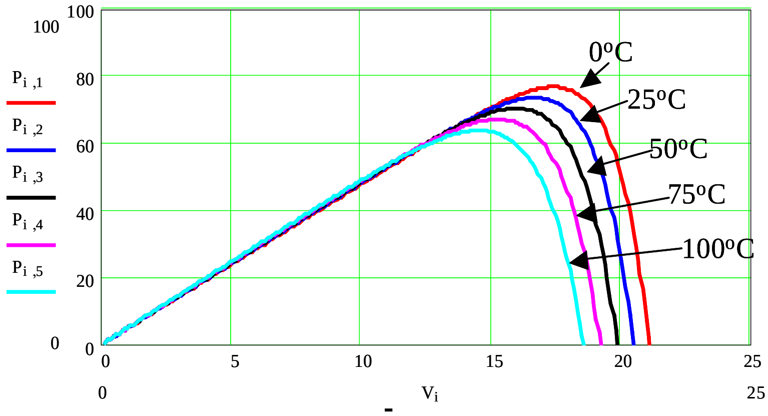
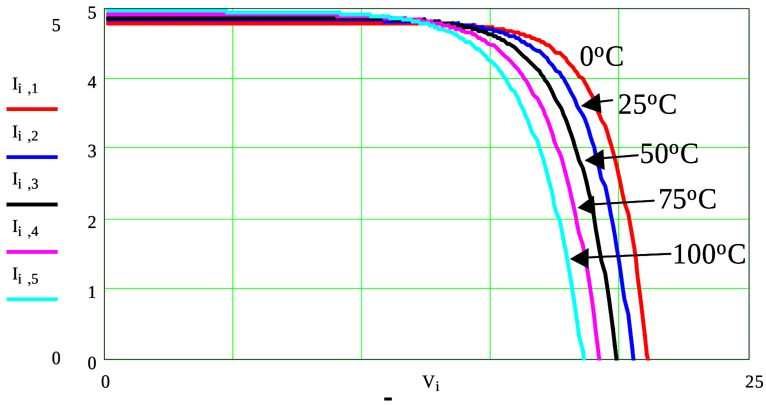


圖 5.2 太陽能電池模組在固定環境溫度(25°C)下，當日照度改變時其：(a)I-V 特性；(b)P-V 特性

經由以上之太陽能電池模組特性模擬曲線可知，日照強度及環境溫度為影響太陽能電池模組輸出功率之兩個重要因素，當太陽能電池模組在瞬息萬變之環境下工作時，溫度與日照強度隨時都可能改變，因此欲使太陽能電池模組能輸出其最大功率，必須隨工作環境改變其工作點，亦即改變太陽能電池模組之電壓及電流，此種控制稱為最大功率點追蹤(MPPT，Maximum Power Point Tracking)控制。最大功率點追蹤之方法有許多種，包括電壓回授法、功率回授法、擾動觀察法、增量電導法、直線近似法等，這些方法從方法之簡單性、準確性及響應速度等來看各有利弊。本計畫採用計算較為準確、響應速度亦非常快速之功率回授法。



(a)



(b)

圖 5.3 太陽能電池模組在固定日照強度(1KW/m^2)下，當溫度變化時其：(a)I-V 特性；(b)P-V 特性

最大功率點追蹤需改變太陽能電池模組之工作電壓或電流，因此必須借助轉換器來達成，圖5.4及圖5.5所示為利用DC-DC轉換器來實現MPPT之兩種方法，圖5.4為利用電壓模式控制，由MPPT控制器計算達到最大功率點所需之太陽能電池模組工作電壓，並以此當成電壓命令控制轉換器之責任週期，使轉換器之輸入電壓追隨此命令達到MPPT之目的。同樣的亦可以採用如圖5.5所示之電流模式控制方式，由MPPT控制器計算達到最大功率點所需之太陽能電池模組工作電流，並以此當成電流命令控制轉換器之責任週期，使轉換器之輸入電流追隨此命令達到MPPT之目的。

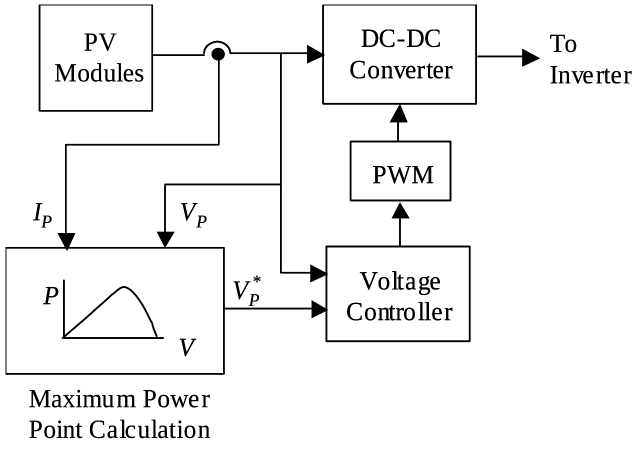


圖 5.4 利用電壓模式控制 DC-DC 轉換器來實現 MPPT 之方法

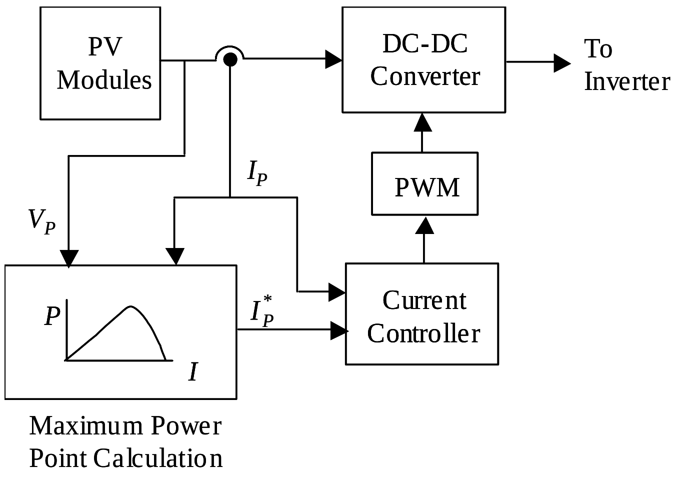


圖 5.5 利用電流模式控制 DC-DC 轉換器來實現 MPPT 之方法

所提之最大功率點追蹤控制方法

本計畫所採用最大功率點追蹤(MPPT)控制之方式為採用電壓模式控制，亦即所計算之最大功率點乃用以產生轉換器之輸入電壓命令(v_p^*)，只要電壓控制器能使輸入電壓追隨此電壓命令即能達到最大功率點追蹤之功能。計算最大功率點所對應之電壓方法如圖5.6所示，乃利用功率-電壓之斜率(dP/dV_p)正負判斷所在之操作區域，並利用適應控制方式調整在各區中電壓命令變化之幅度。當dP/dV_p>0表示操作在第I區，欲得到最大功率可以增加輸入電壓之命令；反之，當dP/dV_p<0表示操作在第II區，欲得到最大功率

可以減少輸入電壓之命令。當dP/dV_p變化較小則進入第III區，本區中需減少電壓之調整量以準確趨近最大功率點。本計畫以數位方式來實現上述輸入電壓命令之計算，如下：

$$v_p^*(m) = v_p^*(m-1) + sign(\Delta P(m)\Delta v_p(m))\, f_i,\ \mathrm{i} = \mathrm{I\ or\ II\ or\ III} \qquad (5.5)$$

其中 m 表示第 m 個取樣週期，f_i 為電壓命令每次之改變值，$f_I>f_{II}$。第 I 區之改變量較大乃因第 I 區之斜率較小，因此需要較大幅度之電壓變化以獲得較佳之追蹤速度；反之，在第 II 區之改變量較小因第 II 區之斜率較大，因此需要較小幅度之電壓變化以使由 II 區回頭趨近最大功率點時不至出現在 I 與 II 區震盪之問題。第 III 區為斜率變化乃至於功率變化非常小之區域，為使最終之工作點越接近最大功率點，當進入此區後 f_{III} 之值調至非常小，一來可以減少震盪二來可以增進精確度。由於太陽能電池之特性變化時間常數非常長，因此 MPPT 之取樣時間可以較轉換器控制迴路高出許多。

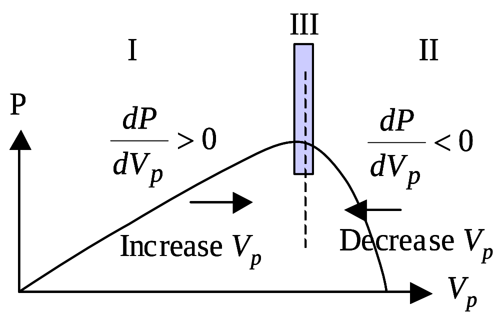


圖 5.6 所提之最大功率點追蹤控制方法

5.2 模擬驗證

系統參數

本計畫所採全橋式DC-DC轉換器之參數如下：

V_p=30~80Vdc，V_d=200V，n=0.1，

V_t=5V/50KHz，L_d=1mH，C_p=1000μF (5.6)

本計畫以V_p=60V當成正常之工作點，根據(2.6)可求得在P = 1KW (I_d=5A)下之系統轉移方程式，為：

$$V_p=60\text{V}：\ H_p(s)=\frac{50(s+4\times10^5)}{s+3331^2},$$

$$V_p=30\text{V}：H_{p1}(s)=\frac{50(s+4\times10^5)}{s+6663^2},$$

$$V_p=80\text{V}：H_{p2}(s)=\frac{50(s+4\times10^5)}{s+2500^2} \quad (5.7)$$

(5.7)中各$H_p(s)$之波德圖如圖4.4所示，選擇PI控制器之z = 2400rad/s (略低於$\omega_{o,min}$)，則由(4.9)可得 k_d=(2400+3331^2)/50(2400+4×10^5)=0.552。MPPT之取樣時間為100Hz，適應控制之f_I=1V、f_{II}=0.2V、f_{III}=0.05V。

PSIM模擬電路與模擬結果

根據上述所得，驗證DC-DC轉換器之PSIM模擬電路建立如圖4.11所示，其中以一電流源來代表太陽能電池模組，模組之輸出電流固定為10A。為驗證DC-DC轉換器確實可以操作在30~80VDC之工作範圍，轉換器之電壓命令設定由一開始之30V突然步級變化為80V。模擬之輸入電壓波形如圖4.12所示，藉由所設計之PV電壓控制器確實能使輸入電壓在0.2s內即能追隨電壓命令之變化，驗證所提之PV電壓控制器設計確實可行。為驗證MPPT控制器之設計，將模擬太陽能電池模組之輸入電流源改成一電壓控制電流源，電壓-電流之特性乃根據前述(4.12)及(4.13)來撰寫，並代入表4.1之參數。MPPT控制器乃根據(4.10)並以C++撰寫再轉換成DLL程式，以便於在PSIM模擬程式中呼叫。包含MPPT及DC-DC轉換器之PSIM模擬程式如圖5.7所示，為驗證在不同日照度下MPPT控制之性能，刻意將日照量由一開始之1KW/m^{2}變化為0.6KW/m^2。模擬之結果如圖5.8所示，由上而下分別表示輸入電壓及其命令、輸入功率、輸入電流及轉換器之控制電壓，由P可知在二

照度下均能追蹤最大之功率點，驗證所提採用適應控制之MPPT控制器確實準確而且響應快速。由電壓追隨其命令之響應知前面之電壓控制器仍然有效。這些均驗證所提DC-DC轉換器系統確實能與MPPT控制結合而且性能均能達到原先設計要求。

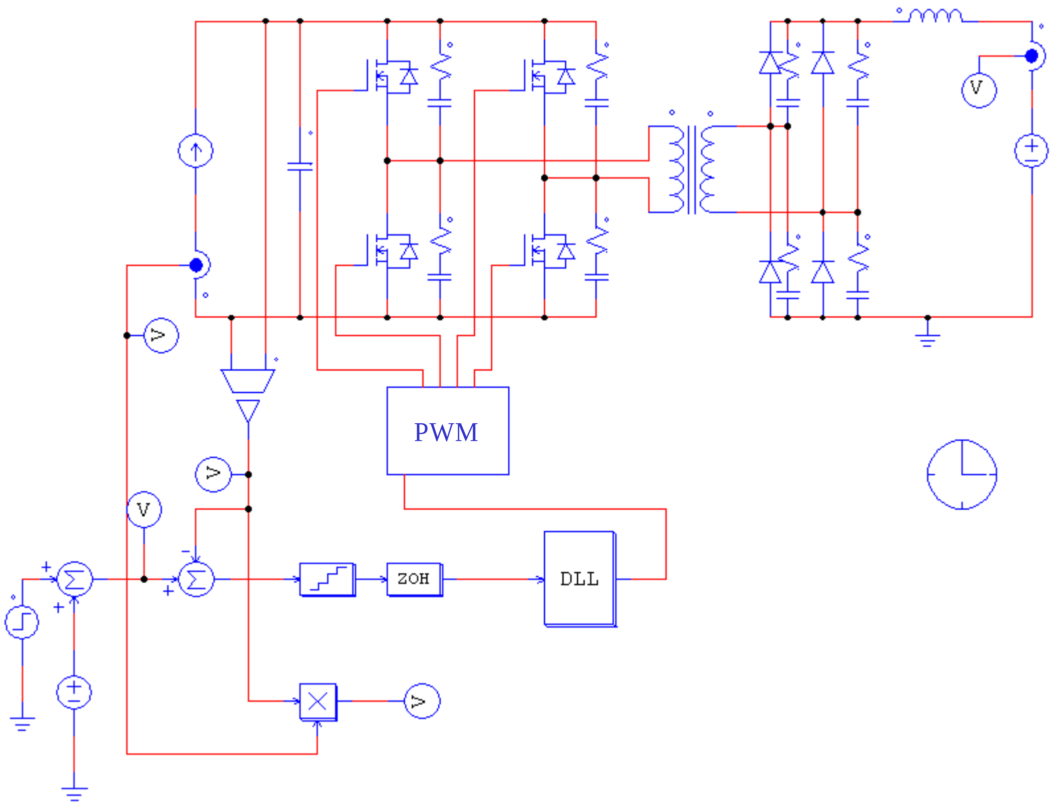


圖 5.7 驗證 DC-DC 轉換器之 PSIM 模擬電路

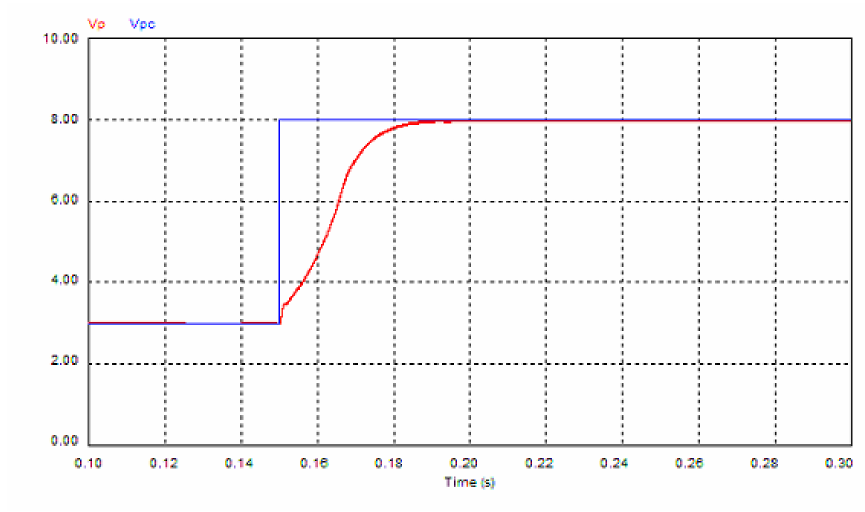


圖 5.8 模擬之輸入電壓波形及其命令

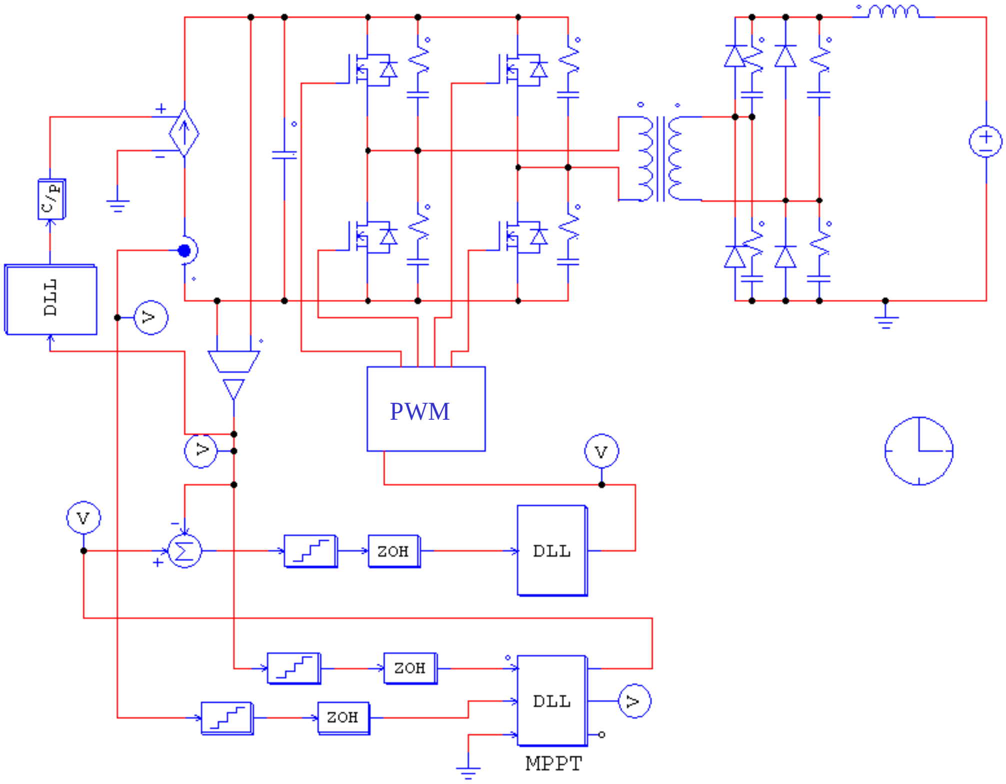


圖 5.9 包含 MPPT 及 DC-DC 轉換器之 PSIM 模擬程式

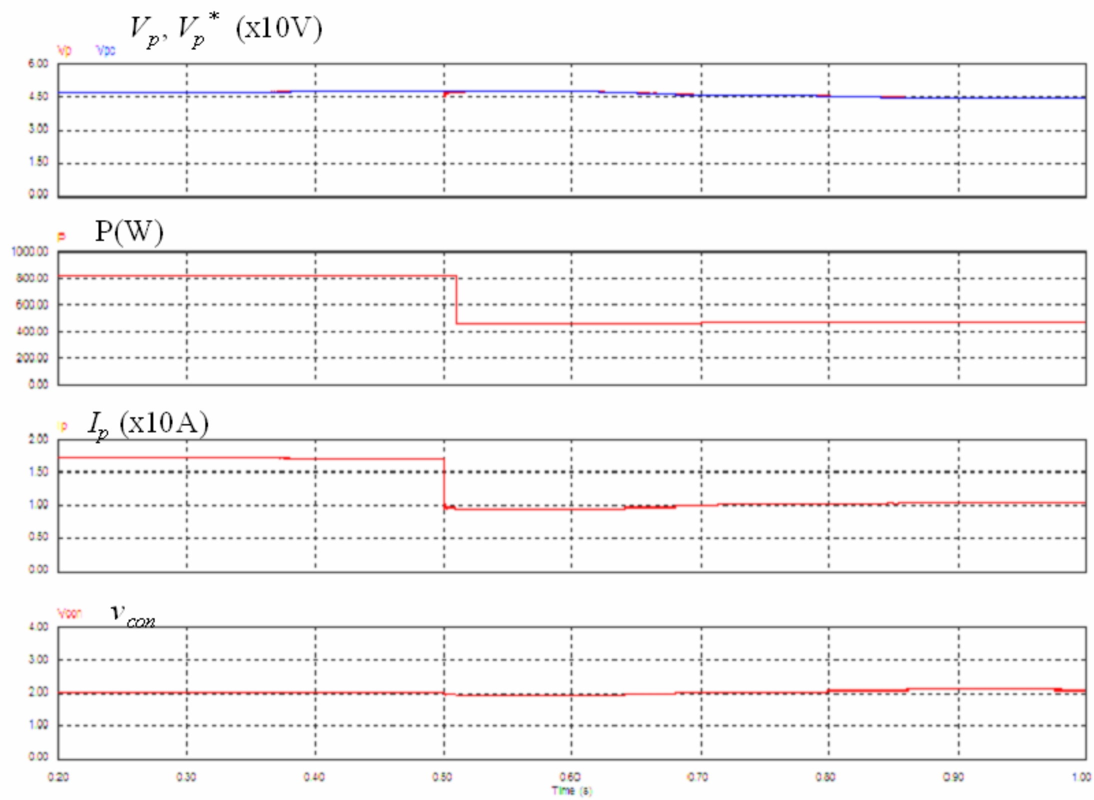


圖 4.10 日照量由 1KW/m^2 變化為 0.6KW/m^2 下 MPPT 控制之模擬結果

六、變流器之原理與設計

6.1 全橋式電壓源變流器與正弦式PWM

所提系統採用如圖6.1所示之單相全橋式電壓源變流器，其開關之切換控制採用如圖6.2所示之單電壓極性(uni-polar voltage)切換PWM。變流器之A臂與B臂有各自之控制電壓($v_{controlA}$及$v_{controlB}$)，但二控制電壓為反相(即$v_{controlA}$ = -$v_{controlB}$)，如圖6.2(a)所示。二控制電壓分別與三角波v_{tri}比較，當控制電壓較三角波大時，上方之開關觸發，轉換器臂之輸出電壓(相對於N點)為V_d；反之則觸發下方之開關，轉換器臂之輸出電壓為0，因此二臂之輸出電壓v_{AN}及v_{BN}分別如圖6.2(b)及圖6.2(c)所示。最後之輸出電壓為二臂之電壓差(即$v_o = v_{AN} - v_{BN}$)，其波形如圖6.2(d)所示，電壓在V_d及0，或是-V_d及0之間變化，因此稱之為單電壓極性切換。此種PWM之特性為：(1)輸出電壓之基本波振幅大小與控制電壓大小成正比，頻率極為控制電壓之頻率(ω_1)：

$$v_{o,1} = m_a V_d \sin \omega_1 t \tag{6.1}$$

其中 m_a 為振幅調制指數，

$$m_a = \frac{\hat{v}_{control}}{\hat{v}_{tri}} \tag{6.2}$$

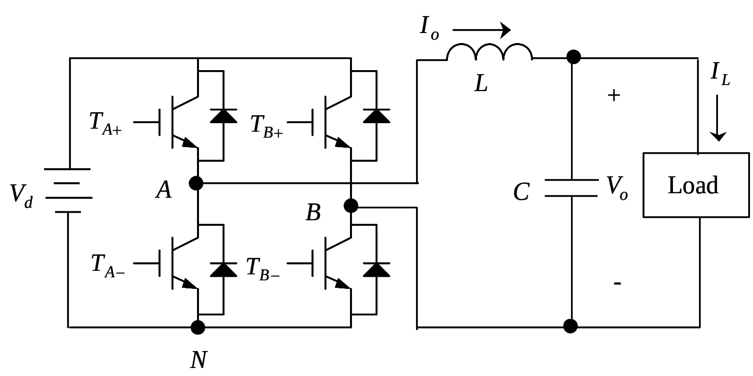


圖 6.1 全橋式電壓源變流器

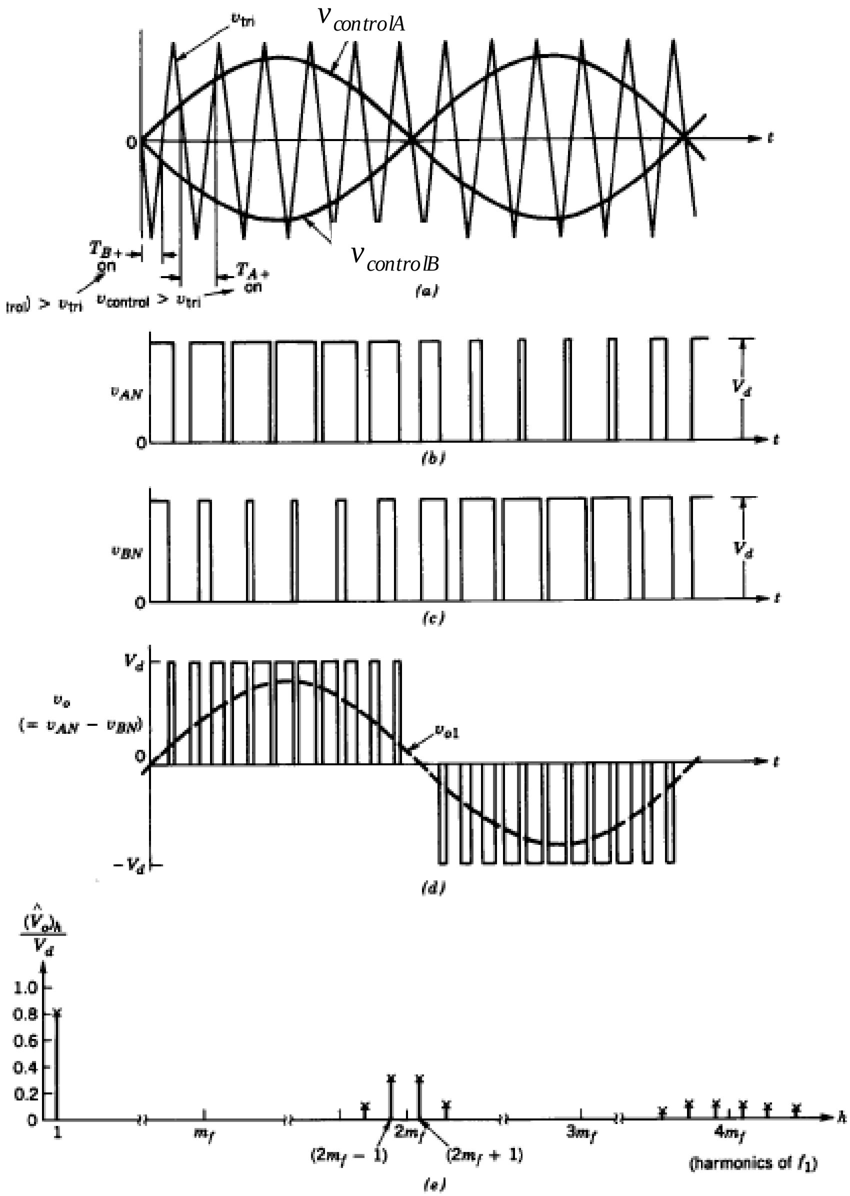


圖 6.2 Uni-polar 正弦式 PWM

(2) PWM 輸出電壓之頻譜如圖 6.2(e)所示，除基本波外，其諧波次數出現在 $h = j(2m_f) \pm k$ 之位置，其中 m_f 為頻率調制指數，

$$m_f = \frac{\omega_s}{\omega_1} \tag{6.3}$$

ω_s 為三角波之頻率，j、k 為整數且 k 為奇數。由之可知諧波出現在兩倍切換頻率之整倍數上，可以等效將切換頻率提高一倍。此外由於電壓之變動

量僅為 V_d，因此輸出濾波器之截止(cut-off)頻率($\omega_c = \frac{1}{\sqrt{LC}}$)可以設計較寬，$L$-$C$ 體積可以大量降低。一般截止頻率設定為小於切換頻率之 1/10，因此採用單電壓極性切換 L-C 之選擇可以設定為：

$$\omega_c = \frac{1}{\sqrt{LC}} = \frac{2m_f\omega_1}{10} \tag{6.4}$$

6.2 變流控制器設計

變流器之電路模型

由圖6.1採用PWM切換之單相全橋式電壓源變流器，可得以下之電路方程式：

$$L\frac{dI_o}{dt} = V_{AN} - V_{BN} - V_o \tag{6.5}$$

若忽略 PWM 之高頻切換項，各臂之輸出電壓可以表示為：

$$V_{AN} = (\frac{1}{2} + \frac{v_{conA}}{2\hat{v}_{tri}})V_d\text{ , }V_{BN} = (\frac{1}{2} + \frac{v_{conB}}{2\hat{v}_{tri}})V_d \tag{6.6}$$

其中 v_{conA}、v_{conB} 為 A、B 臂之控制電壓，$\hat{v}_{tri}$ 為 PWM 三角波之振幅。由於單電壓極性切換下 v_{conA}=-v_{conB}=v_{con}，將之與(6.6)共同代入(6.5)可得：

$$L\frac{dI_o}{dt} = k_{pwm}v_{con} - V_o \tag{6.7}$$

其中 $k_{pwm} = \frac{V_d}{\hat{v}_{tri}}$ ，可以視為變流器之電壓增益。另外由電容電流亦可得：

$$C\frac{dV_o}{dt} = I_o - I_L \tag{6.8}$$

變流器之控制器可根據(6.7)及(6.8)來加以設計。

電感L值之選擇必須以變流器所能轉移之最大功率來計算，變流器之輸出實功率為：

$$P_o = \frac{(k_{pwm} v_{con} - V_o)}{2\omega_1 L} V_o \sin\delta \tag{6.9}$$

其中δ為 v_{con} 與 V_o 電壓之夾角。考慮 PWM 控制電壓之相角可以任意調整，而且 PWM 在任何情況均位於線性調制區(即 $m_a \le 1$)，則最大輸出功率為：

$$P_{o,\max} = \frac{(V_d - V_{o,\max})V_{o,\max}}{2\omega_1 L} \tag{6.10}$$

最大之 L 可由最大輸出功率來選擇。一旦 L 決定，輸出電容 C 亦可以利用(6.4)決定。

電感電流控制器設計

電流迴路設計如圖6.3所示，其中k_v及k_s分別為電壓及電流之感測增益，k_q為類比轉數位之增益。若感測電路為-1.65~1.65V(5.3V之系統)且系統數值以N位元來表示，則

$$k_q = \frac{2^N}{3.3} \tag{6.11}$$

在數位控制下PWM之責任週期若仍以N位元來表示，則各開關之責任週期為：

$$D_{A+} = (2^{N-1} + \frac{v_{con}}{2^N})\text{，}D_{B+} = (2^{N-1} - \frac{v_{con}}{2^N}) \tag{6.12}$$

因此(6.7)可表示為：

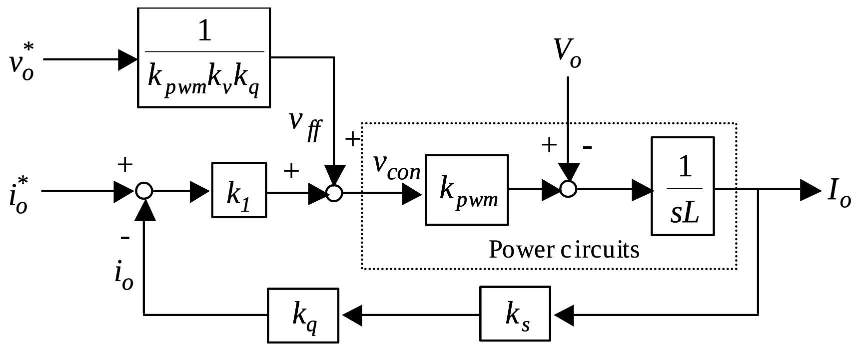


圖 6.3 電流迴路控制方塊圖

$$L\frac{dI_o}{dt} = (D_{A+} - D_{B+})V_d - V_o = \frac{v_{con}}{2^{N-1}}V_d - V_o = k_{pwm}v_{con} - V_o \quad (6.13)$$

k_{pwm} 值必須修正為：

$$k_{pwm} = \frac{V_d}{2^{N-1}} \quad (6.14)$$

所提之電流控制器採用迴授配合前向控制(feedforward control)方式，利用電壓命令 v_o^* 乘上增益 $1/k_{pwm}k_v k_q$ 來直接抵消輸出電壓 V_o 對於電流迴路之擾動。電流迴路之響應可由電流迴授迴路求得為：

$$\frac{i_o^*}{i_o} = \frac{\dfrac{k_{pwm}k_s k_1 k_q}{L}}{s + \dfrac{k_{pwm}k_s k_1 k_q}{L}} = \frac{u_I}{s + u_I} \quad (6.15)$$

此處 u_I 即為電流迴路之頻寬：

$$u_I = \frac{k_{pwm}k_s k_1 k_q}{L} = \frac{2V_d k_s k_1}{3.3L} \quad (6.16)$$

其可以利用電流誤差放大器之增益 k_1 來加以設定，一般電流迴路之頻寬以不超過切換頻率之 1/4 為準則，本計畫採用 1/5。

電壓控制器設計

為在市電正常下，變流器除須將太陽能所發之電力轉移至交流測外，仍須對補償系統內轉換器之損失，因此變流器之外迴路如圖6.4所示為一直流電壓控制器，以維持直流鏈電壓之方式達到交-直流電力轉換之平衡。直流電壓控制器利用直流鏈電壓與其參考值之誤差經控制器G_d調整後乘上與市電電壓同相之正弦波sinω$_1$t，得到變流器之實功電流命令i_{op}^*。i_{op}^*再加上輸出濾波電容之虛功補償電流i_q^*得到變流器之電感電流命令。電容之虛功補償電流i_q^*可根據以下方式設定：

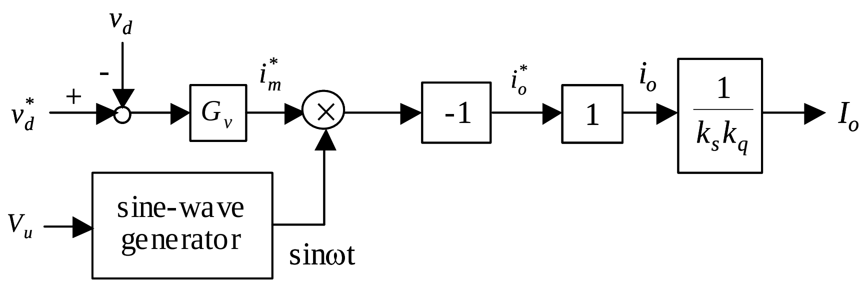


圖 6.4 直流電壓之控制方塊圖

$$i_q^* = \omega_1 C V_o k_s k_q \cos \omega_1 t \qquad (6.17)$$

由於直流鏈電壓包含二次漣波，為使此經誤差調整放大之電流命令為低失真，控制器G_d採用type II之補償器以使在120Hz附近之迴路增益仍高以衰減此二次漣波。若忽略輸出濾波電容之電流，I_o為與V_o為同相；若忽略變流器之損失，變流器直流側之輸入功率等於交流側之輸出功率，即：

$$V_d I_d = V_o I_o / 2 \qquad (6.18)$$

若假設變流器直流側可視為一等效電阻為$R(=V_d / I_d)$之直流負載如圖6.5所示，則(6.18)可以表示為：

$$\frac{V_d^2}{R} = \frac{V_o I_o}{2} \tag{6.19}$$

故

$$\frac{\Delta V_d}{\Delta I_o} = \frac{R V_o}{4 V_d} \tag{6.20}$$

再考慮直流電容之效應可得：

$$\frac{V_d(s)}{I_o(s)} = \frac{R V_o}{4 V_d} \frac{R}{1 + s C_d R} = \frac{R^2 V_o / 4 V_d}{1 + s C_d R} = k_{dc} \frac{1}{s + a} \tag{6.21}$$

其中：

$$a = \frac{1}{C_d R},\ k_{dc} = \frac{R V_o}{4 C_d V_d} \tag{6.22}$$

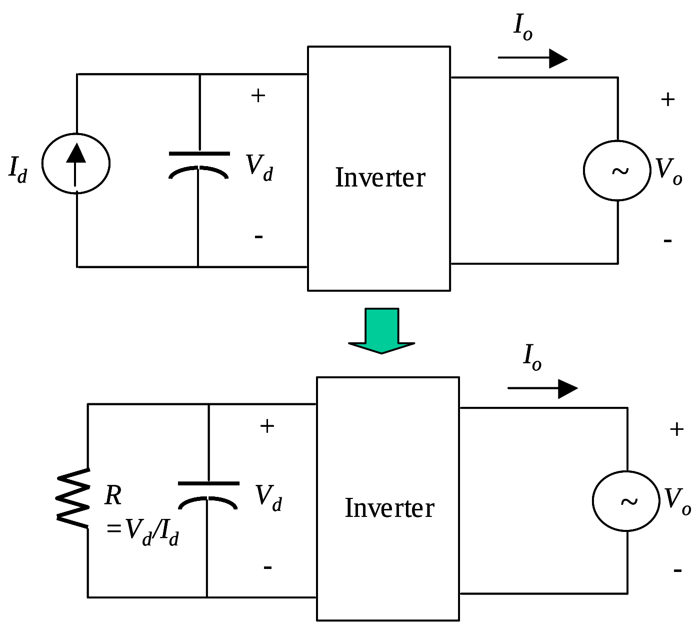


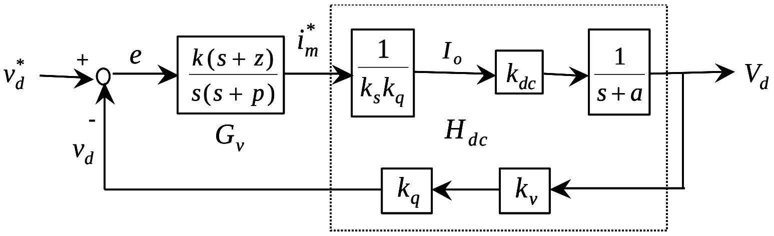
圖 6.5 變流器直流側可視為一等效電阻為 $R(=V_d / I_d)$之直流負載

因此電壓控制迴路之方塊圖如圖6.6(a)所示。根據圖6.6(a)可得包含轉換器及感測增益之所謂受控體之轉移函數H_{dc}(s)，並將其在最大功率轉移(相當

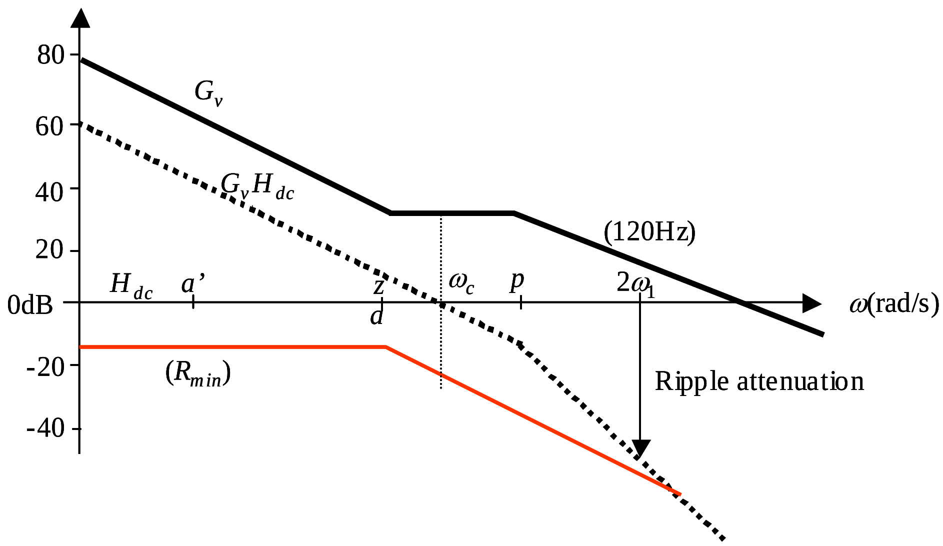
於R_{min})及最小功率轉移(相當於R_{max})等二極限條件下之波德圖繪出如圖6.6(b)，type II補償器($G_v=\frac{k(s+z)}{s(s+p)}$)之設計可根據$H_{dc}$(s)利用K-factor之方法設計。首先以最大功率轉移曲線(R_{min})選擇迴路增益G_vH_{dc}之crossover frequency ω_c使之遠低於$2\omega_1$(120Hz)以便於在$2\omega_1$時有較低之增益以衰減二次漣波，由ω_c時H_{dc}之增益亦可以得到$G_v(\omega_c)$之增益用以決定增益k。接著設定type II補償器之極點及零點滿足：

$$K = \frac{p}{\omega_c} = \frac{\omega_c}{z} \tag{6.23}$$

K值之選擇需使$p < 2\omega_1$以便於達到較佳之二次漣波衰減，Z值應儘量大以獲致低頻時較大之迴路增益以降低電壓暫態響應之變化量，因此二者之選擇衝突故需作一折衝。相位邊限(PM, phase margin)在此不是問題，PM為：



(a)



(b)

圖 6.6 (a)電壓控制迴路方塊圖；(b)設計電壓迴路之波德圖

$$PM = 90^o - \tan^{-1}\left(\frac{\omega_c}{a}\right) + \tan^{-1}(K) - \tan^{-1}\left(\frac{1}{K}\right) \qquad (6.24)$$

G_v 數位控制程式之撰寫

對於type II補償器：

$$\frac{y}{e} = \frac{k(s+z)}{s(s+p)} \qquad (6.25)$$

欲寫成數位控制程式，可以最簡單之 backward Euler 方法撰寫，亦即：

$$\frac{y(n)-2y(n-1)+y(n-2)}{h^2} + \frac{p[y(n)-y(n-1)]}{h} = \frac{k[e(n)-e(n-1)]}{h} + kze(n) \qquad (6.26)$$

其中 h 為取樣時間，n 表示取樣序列。(6.26)可再整理為：

$$y(n)=\frac{1}{1+hp}[(2+hp)y(n-1)-y(n-2)+(hk+h^2kz)e(n)-hke(n-1)] \quad (6.27)$$

6.3 實際系統設計之數值計算

本計畫與變流器相關之電路參數如下：

V_d=200V_{dc}， $V_o=110\sqrt{2}\pm10\%=140\sim171V$,

取樣頻率f_s=10KHz (h=0.1ms)， C_d=1000μF，

變流器轉移功率範圍P_o=200W~2KW(R=200Ω~20Ω)，

$$N=10\text{ 位元，}k_s=0.1\text{，}k_v=0.01 \quad (6.28)$$

由(6.4)可得$LC=2.5\times10^{-8}$。由(6.10)可得L_{max}=4.2mH，此處採用L=2mH，故C=25μF。由(6.11)及(6.14)分別得k_q=310.3，k_{pwm}=0.39，故若電流迴路之頻寬u_I設為f_s/5=2000Hz(=12566.4rad/s)，則由(6.16)可得電流控制器之增益k_I=2.07。對於電壓控制器之設計，$H_{dc}(s)$可表示為：

$$H_{dc1}(s)=\frac{k_{dc}}{k_s k_q}\frac{1}{s+a}=\frac{1258}{s+5},\ R_{max}=200\Omega$$

$$H_{dc2}(s)=\frac{k_{dc}}{k_s k_q}\frac{1}{s+a}=\frac{12580}{s+50},\ R_{min}=20\Omega$$

以$H_{dc2}(s)$曲線選擇ω_c = 100(rad/s)，選擇K = 2使p = 200(rad/s)且z = 50(rad/s)，由$G_v(\omega_c)=1/H_{dc2}(\omega_c)$可得$G_v$之$k$ = 0.024。相位邊限由(6.24)可得為PM=63.4°。G_v之數位程式撰寫將以上之數據代入並由(6.27)可得。

6.4 PSIM之模擬

變流器本身之模擬

根據上述之設計，本計畫先行以PSIM軟體模擬，PSIM之變流器電路建立如圖6.7所示，其中變流器與市電並聯，負載為15Ω之電阻，在110V_{rms}市

電電壓下負載功率為806W。在直流側部分以一電流源(I_d)來模擬由DC-DC轉換器傳送過來之電流。變流器之G_v乃以visual C++撰寫再轉成DLL檔案，C++程式如圖6.8所示，乃根據(6.27)撰寫。電流控制器建立如圖6.7之方塊圖所示，圖6.7中單電壓極性切換PWM之建立詳細如圖6.9所示，乃根據(6.12)來實現，觸發信號之產生以一controlled之mono-stable方式進行。

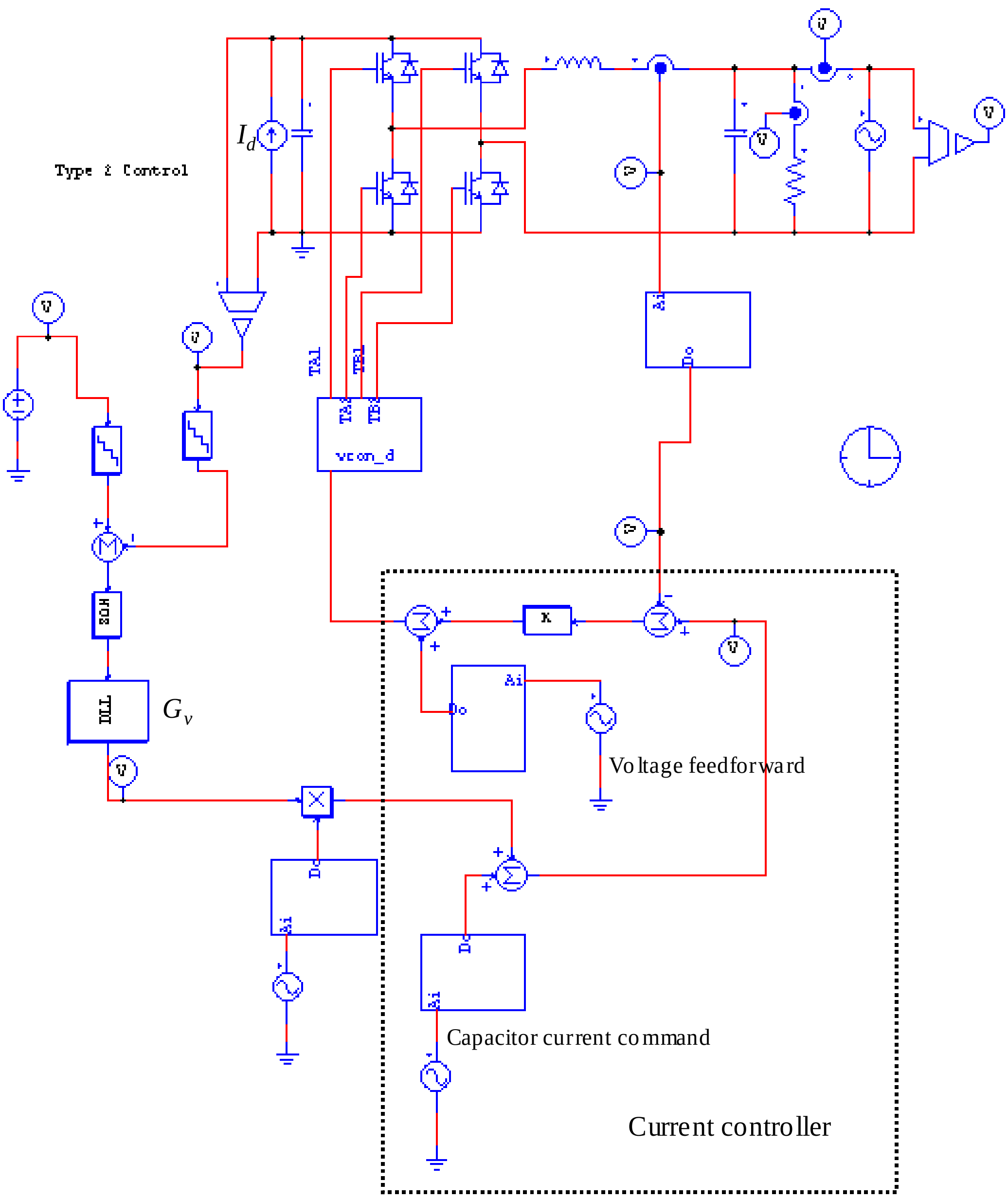


圖 6.7 PSIM 之變流器模擬電路

```
#include <math.h>
__declspec(dllexport) void simuser (t, delt, in, out)
double t, delt;
double *in, *out;
{
      static double ek=0., ekp=0., yk=0., ykp=0., ykp2=0;
   ek = in[0];
   yk = (2.018*ykp - ykp2 + 1.003*ek - ekp)/1.018;
   out[0] = -0.01 * yk;
      ykp2 = ykp;
      ykp = yk;
      ekp = ek;
}
```

圖 6.8 C++程式之 G_v 撰寫

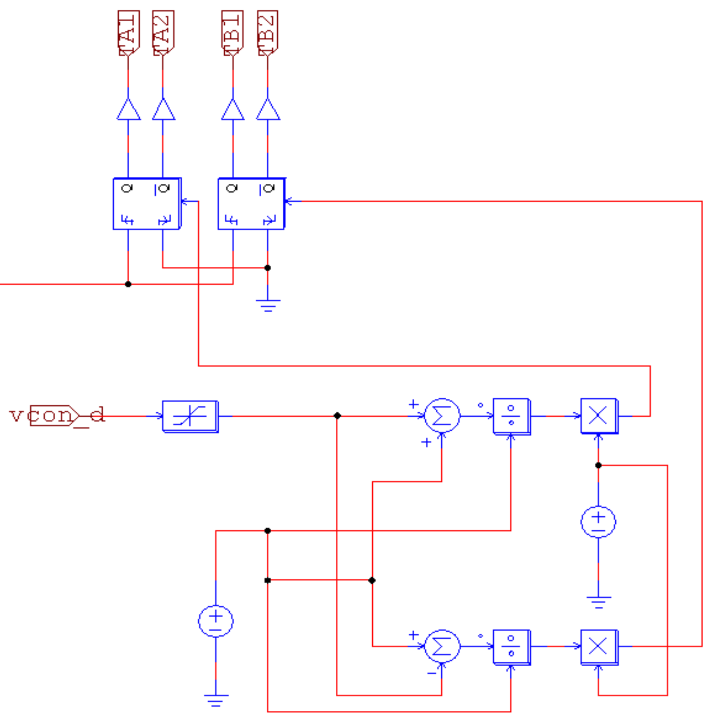


圖 6.9 單電壓極性切換 PWM 電路之建立

Case 1: 負載電力大於太陽能所發之電力

令I_d=3A，相當於由DC-DC轉換器所送過來之功率為3A×200V=600W，其小於負載功率(806W)。模擬結果如圖6.10所示，圖中由上而下依序顯示了直流電壓之調整、負載與變流器電流、輸入電壓及電流、數位控制下之電感電流追蹤其命令等響應。由電感電流緊密追蹤其命令之響應可看出電流迴路之成功，由電感電流之正弦亦可驗證type II控制器衰減二次漣波降低電流失真之功效。由直流電壓之調整亦可驗證所設計之type II補償器及以C++所撰寫之程式確實可行。由於負載電力大於太陽能所發之電力因此電感電流小於負載電流，故輸入電流自動補足此不足，輸入電流因此與市電電壓同相，而且電流為低失真。

Case 2: 負載電力等於太陽能所發之電力

令I_d=4A，相當於由DC-DC轉換器所送過來之功率為4A×200V=800W，約等於負載功率(806W)。模擬結果如圖6.11所示，前述之電流迴路、電壓迴路等依然特性良好。由於負載電力等於太陽能所發之電力因此電感電流等於負載電流，故輸入電流幾乎為零。

Case 3: 負載電力大於太陽能所發之電力

令 I_d=6A，相當於由DC-DC轉換器所送過來之功率為6A×200V=1200W，大於負載功率(806W)。模擬結果如圖6.12所示，前述之電流迴路、電壓迴路等依然特性良好。由於負載電力大於太陽能所發之電力因此電感電流大於負載電流，多餘之電流則饋入市電，故輸入電流與市電電壓反相，而且電流為低失真。

變流器與 DC-DC 轉換器結合並作 MPPT 之模擬

接著將第三章採用MPPT控制之DC-DC轉換器加入，作一完整系統之模擬，PSIM模擬電路建立如圖6.13所示。為了觀察最大功率點追蹤性能，刻意在模擬中對日照度作一步級變化(1KW/m^2->0.8KW/m^2)。模擬之結果如圖

6.14所示，圖中由上而下依序顯示了太陽能電池電壓之調整、太陽能電池發電之功率、直流電壓之調整、負載與變流器電流、輸入電壓及電流等響應。由太陽能電池電壓及其命令之波形可看出DC-DC轉換器確實能達成電壓控制並執行MPPT控制；由太陽能電池發電之功率(800W->600W)可知日照度確實有步級變化；由負載與變流器電流可看出變流器確實仍正常工作，由一開始約等於負載電流變為低於負載電流，由輸入電壓及電流等響應亦可觀察市電在發電量低於負載需求時會提供不足之電流。輸入電流亦能維持與市電電壓同相，而且為低失真。這些均驗證所提變流器之控制技術仍然可以應用在整個系統而且特性良好。圖6.15所示為圖6.14之最大功率點追蹤之P-V圖，為證明確實有追到最大功率點，圖中亦將電池之P-V特性圖繪出。

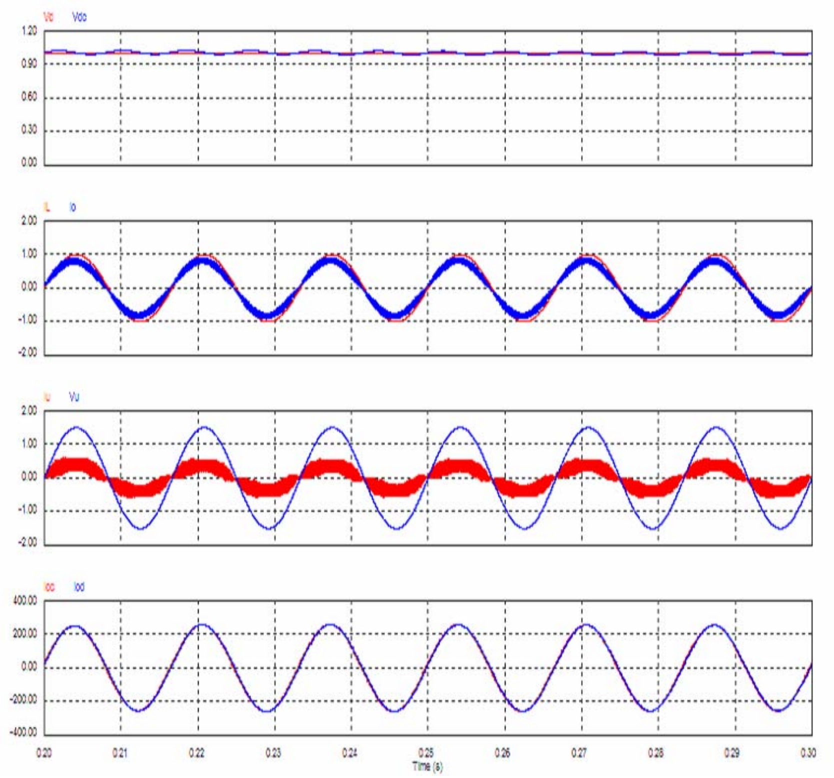


圖 6.10 負載電力大於太陽能所發電力之模擬結果

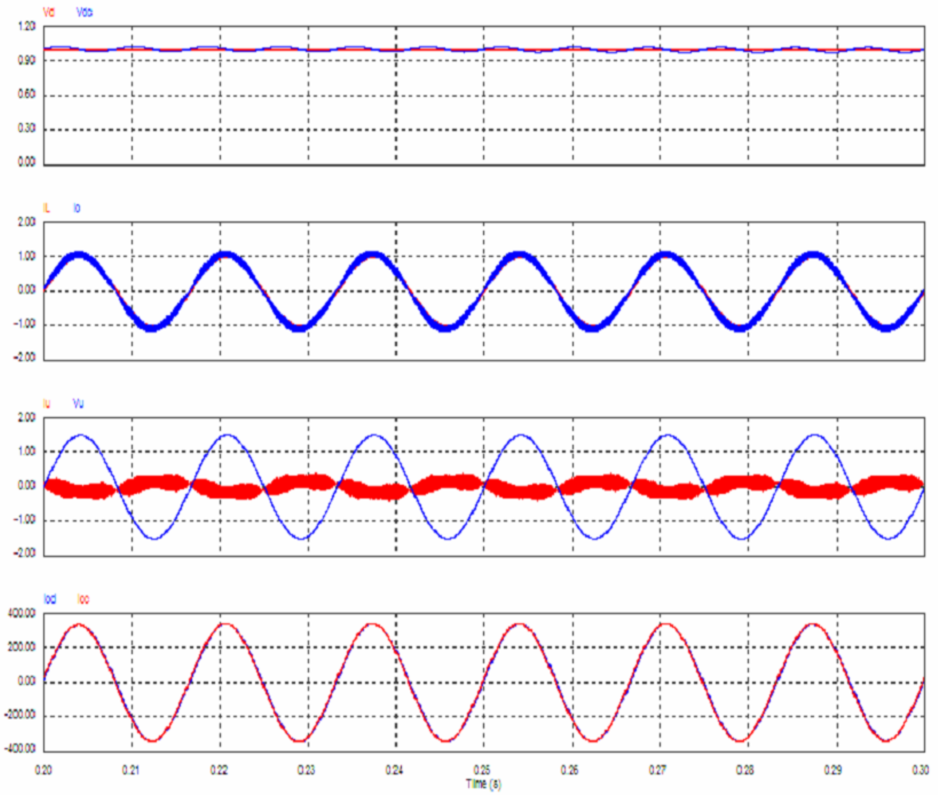


圖 6.11 負載電力等於太陽能所發電力之模擬結果

由模擬結果可驗證本文所提出的數位式最大功率追蹤控制，擁有寬廣的電壓輸入範圍及高效率轉換，適用於偏遠地區無人操控之監測及通訊站等多項機動性之電源解決方式，並可做為未來發展高效能環保發電的預備工作。

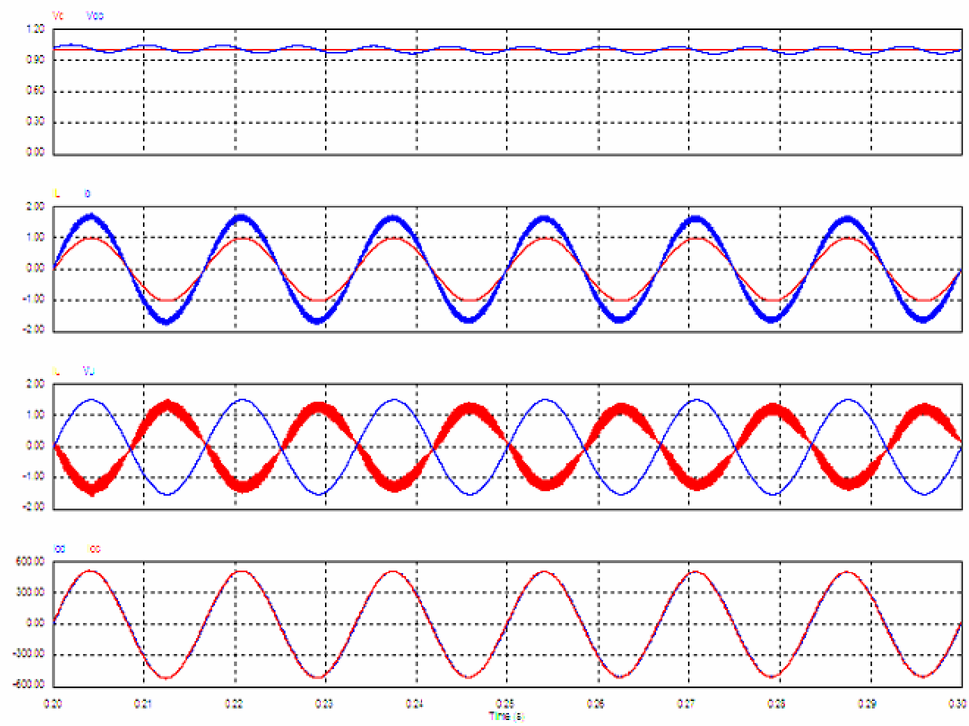


圖 6.12 負載電力小於太陽能所發電力之模擬結果

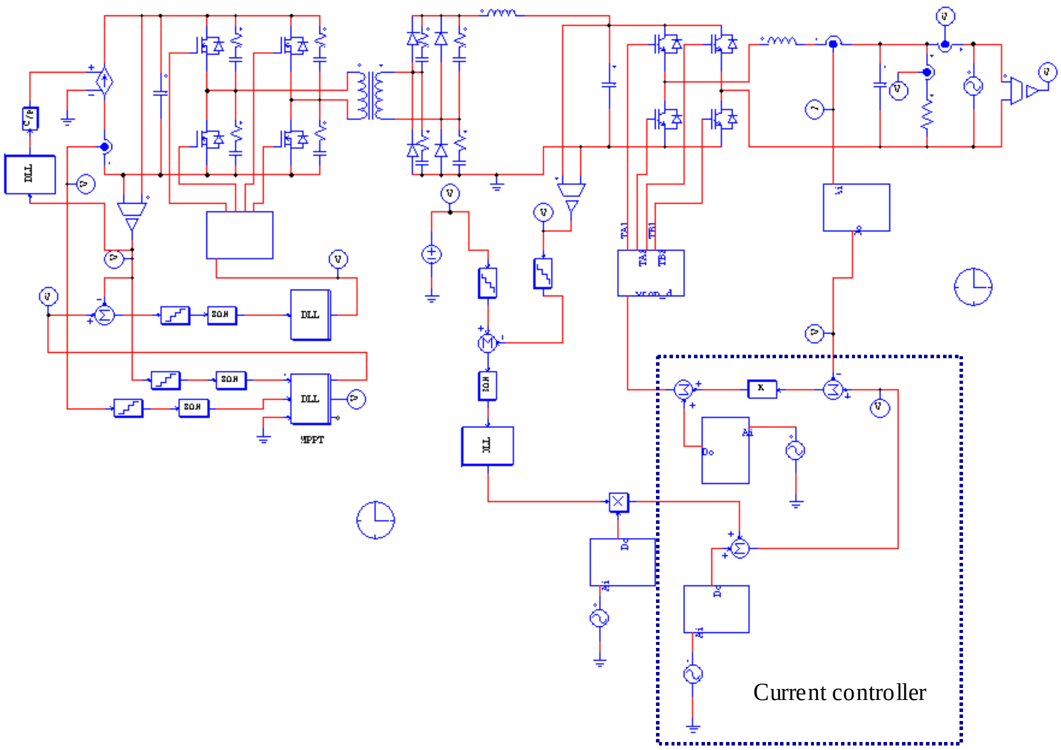


圖 6.13 一完整系統之模擬電路

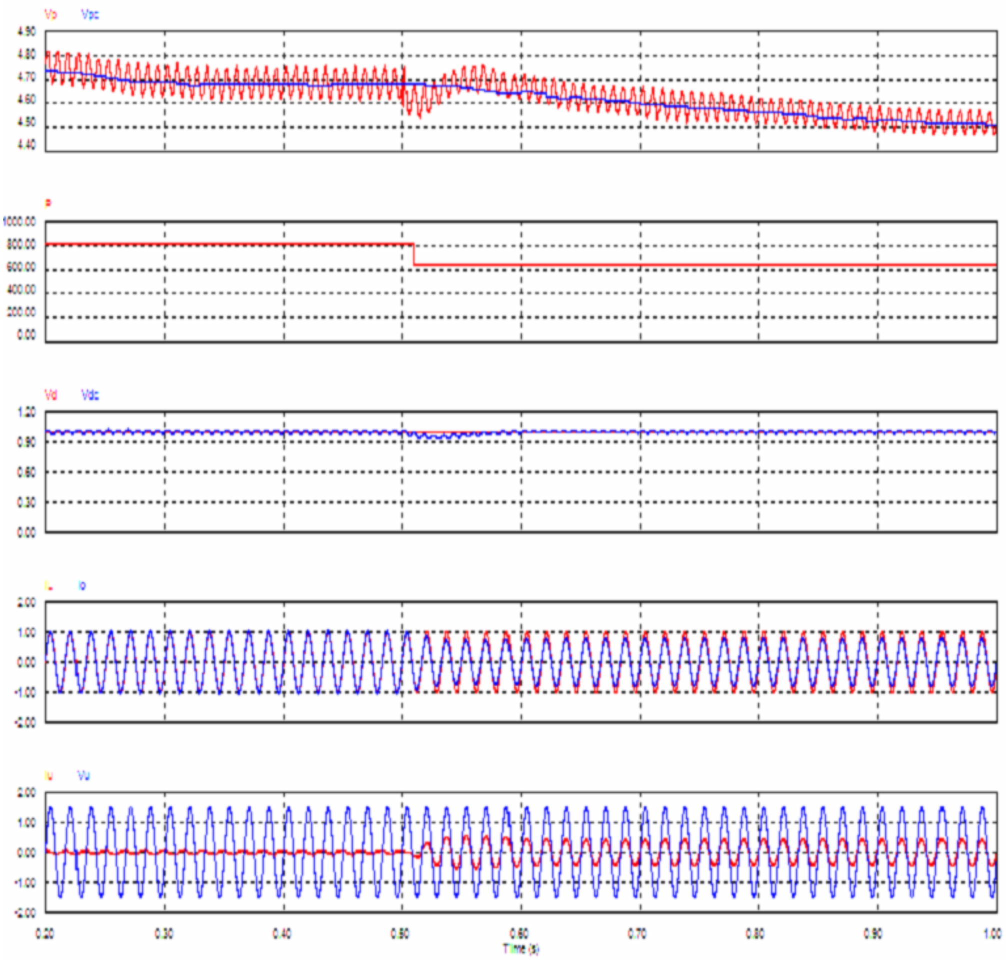


圖 6.14 一完整系統之模擬結果

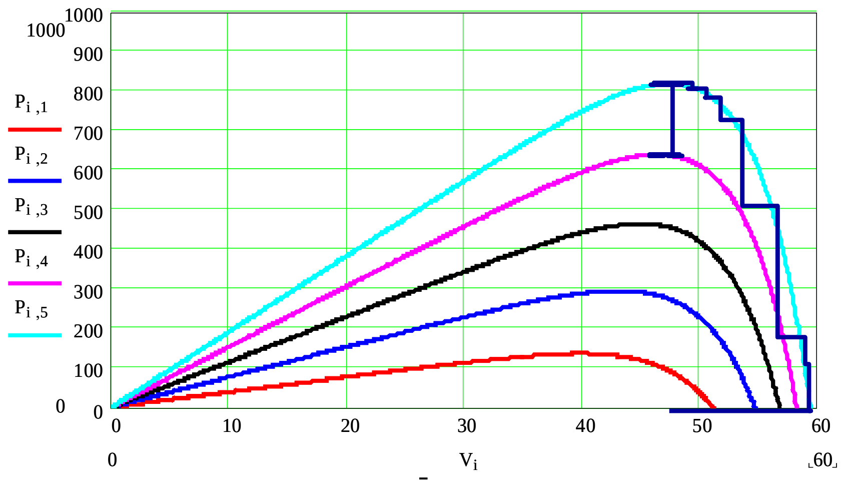


圖 6.15 最大功率點追蹤之模擬結果

七、太陽光變頻器併網控制之原理與模擬

光伏電池輸出特性探討

太陽能電池主要是應用光伏效應(photo voltaic effect)將光能量轉換為電能，除其材料不同及使用後劣化問題外，如日照強度、溫度、濕度等不同之環境條件下，皆會影響其輸出特性。為使太陽能電池發揮其最佳效用，故需探討其輸出特性，一般可視其為PN二極體，其輸出電流可表示為：

$$I = I_{SC} - I_{SAT}[\exp(\frac{qV}{nkT_S}) - 1] \tag{7.1}$$

V：輸出電壓

I：輸出電流

I_{SC}：光發生之最大電流

I_{SAT}：二極體反向飽和電流

q：儲存電荷量

k：波茲曼常數

T_S：晶體溫度

由於輸出電壓電流之非線性化，故控制尋求太陽能板之最大輸出功率點(maximum power point: MPP)，成為前級功能設計重點；升壓式直流轉換器屬單開關直流轉換器，其線路簡單控制容易，且具高效率特點，故本研究利用升壓式直流轉換器於太陽能板之後，利用脈波寬度調變(PWM)原理，依不同的輸入電壓及電流，以閉迴路控制，加入最大功率輸出點追蹤技術，調整開關之責任週期比，提供穩定之直流鏈電壓，同時因其輸出具有一個飛輪二極體，面對負載變化時之直流鏈電壓上升下，可抵擋直流鏈電流回灌至太陽能板，造成太陽能板之損壞。

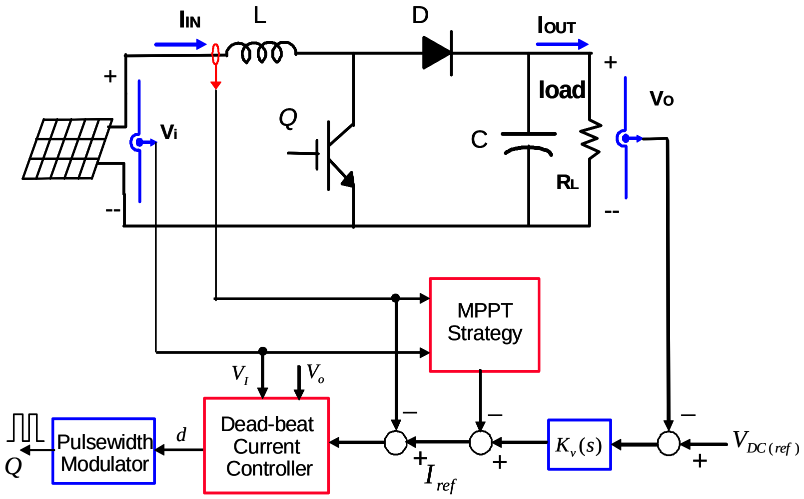


圖 7.1 升壓式直流轉換器電路暨控制方塊圖

升壓式直流轉換器之探討與分析

升壓式直流轉換器控制架構如圖7.1所示，輸入輸出電壓比與責任週期比D_1關係為

$$\frac{V_O}{V_I}=\frac{1}{1-D_1}=\frac{I_{IN}}{I_{OUT}} \tag{7.2}$$

在電壓迴路產生的電流參考命令中加入最大功率追蹤成分，在配合Dead-Beat電流控制器，如圖7.2所示，快速調整電感電流，達到最大功率輸出點，同時可輸出穩定的直流鏈電壓，電流控制器設計依據如下式：

$$1-d=\frac{V_I-\Delta V_L}{V_{DC}} \tag{7.3}$$

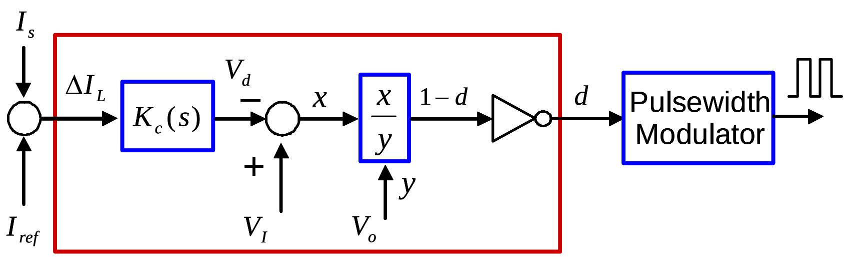


圖 7.2 前級之 Dead-beat 電流控制器

雙半橋式變流器之探討與分析

變流器之功能在於將前級之直流鏈輸出電壓，轉換成與市電相同大小、相同頻率及相位的交流電壓，以供應負載之交流電源，同時藉由併聯技術直接可將太陽能發電功率回送至市電；然而，換流器調變中會受前級直流鏈電壓變動、輸出級非線性負載、及切換元件之非理想特性等因數影響，故調變後的輸出電壓或電流往往無法追隨參考命令，嚴重影響輸出電壓之總諧波失真及整機性能；因此必須透過電壓或電流控制迴路來調整，使變流器能穩定輸出交流電壓。

雙半橋式變流器是由兩組半橋式變流器組成，兩者產生對地反相輸出電壓，提供AC110V，再以差壓方式得到AC220V，此硬體設計及控制，相較於三相六開關晶體控制，可簡化硬體之複雜度及控制之穩定性，以下就以單一半橋式變流器討論之。一般而言，其脈波寬度調變可分為單極性切換(Unipolar PWM)與雙極性切換(Bipolar PWM)，產生之脈寬調變電壓後，經過LC濾波電路得到基頻正弦信號。慎選LC之值是必要的，電感L的值決定於電感漣波大小之限制，由下式決定：

$$\Delta i_{L(\max)} = \frac{V_{DC}}{4Lf_S} \tag{7.4}$$

$$\Delta v_{O(\max)} = \frac{V_{DC}}{32LCf_S^2} \tag{7.5}$$

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{7.6}$$

f_S：變流器切換頻率

f_r：輸出濾波器共振頻率

V_{DC}：直流鏈電壓

$\Delta i_{L(max)}$：最大電感漣波電流

$\Delta v_{O(max)}$：輸出電壓漣波

輸出電壓漣波大小即決定於濾波電容值，直流鏈的最大輸出電壓漣波決定於開關頻率與LC諧振頻率的比值。一般而言，為了降低LC諧振頻率對閉迴路動態響應的影響，必需將LC諧振頻率設定高於閉迴路系統的頻寬，降低諧振頻率對動態響應可能產生的系統震盪。

預測型電流控制器之設計

半橋式變流器多迴路控制方式如圖7.3所示，採用雙迴路控制架構，內迴路為電流內迴路，它是一種快速作用電流預測之Dead-Beat電流控制器，使得輸出電壓與參考電壓同相且成正弦波形。外迴路為電壓控制迴路，調節輸出電壓有效值的誤差，故常加入其有效值補償項進行修正，以應付較大的整流性負載，補償電壓失真現象，降低輸出電壓之總諧波失真。

半橋式變流器輸出電感L_o的電壓變動量決定其電流的瞬間變動量，假設開關週期遠小於電流內迴路的時間常數，則電感電壓變動可表示如下：

$$\Delta V_L = (\frac{V_{DC}}{2} - V_O) \cdot d - (V_O + \frac{V_{DC}}{2}) \cdot (1 - d) \tag{7.7}$$

相對應的開關責任比為

$$d - 0.5 = \frac{\Delta V_L + V_O}{V_{DC}} \tag{7.8}$$

根據上述關係可發展為預測型電流控制器如圖7.4所示，具快速響應及零穩態誤差之優點，達成高頻寬電流迴路之設計，非常適合DSP的軟體實現。

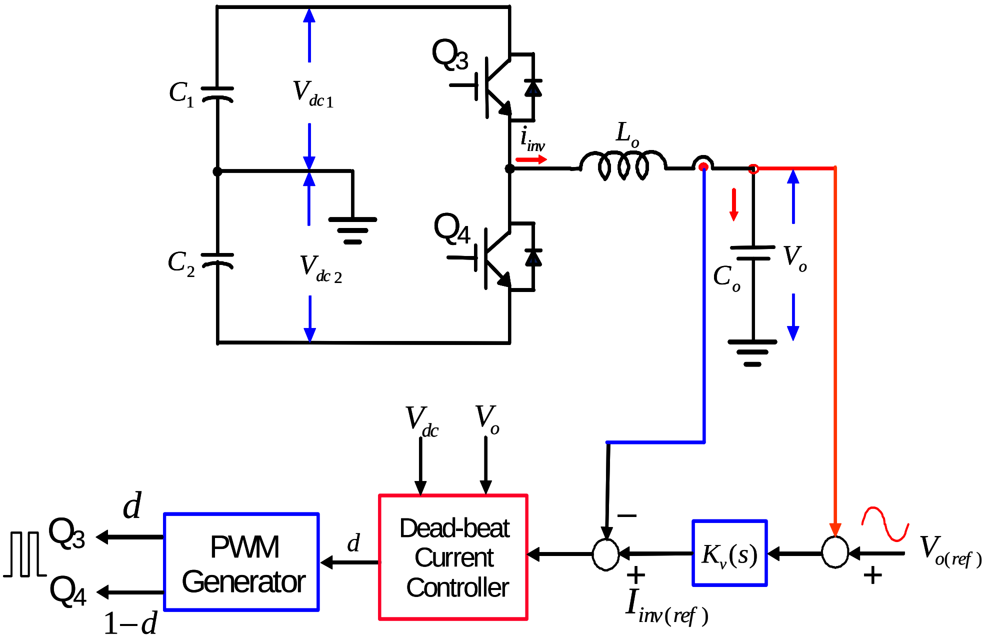


圖 7.3 變流器之控制方塊圖

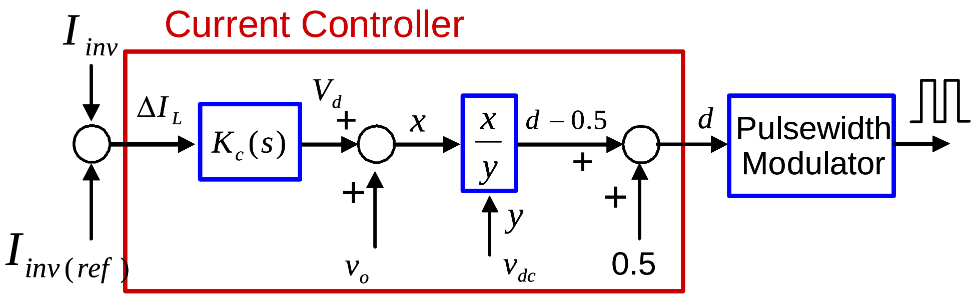


圖 7.4 變流器之預測型電流控制器

輸出電壓之非平衡控制

一些類比元件所存在的直流偏移現象及系統初始情況的不平衡現象，造成上下臂兩電容電壓不平衡，造成輸出交流正弦電壓含有直流準位，除造成輸出中性點零電位之飄移外，更造成電感容易飽和之嚴重後果，故需藉由電壓迴路中之直流準位修正，方可去除輸出的直流成分。透過不平衡控制，對於負載上的不對稱亦有相同的效果，適應單相三線制輸出，對於中性線設計較細者，以不平衡控制調節中性線電流之方法，將成為未來討論之重點，且方便於將來併聯時之電流控制技術。

本研究以DSP數位控制板配合直流升壓式轉換器與雙半橋式變流器之功率級架構，整合為一個以DSP為基礎之全數位控制實驗發展系統，實現所設計之數位控制器。預定採用DC12V太陽能板每串六塊串連後再併聯方式，提供DC72V輸出電壓及大電流，直流鏈電壓訂為DC 400V，六個470μF構成直流鏈電容705μF，開關頻率為24 kHz，輸入電感2.5mH，輸出電感1mH，輸出電容36μF，再以DSP為控制器實現軟體控制策略，進行不同情況下之實驗驗證。

圖7.5為模擬單相三線制輸出波形，可提供兩組AC110V及一組AC220V電壓之交流電源；圖7.6則模擬輸出為各1kW之平衡負載電壓波形，其中性線電流恰為0；圖7.7則模擬不平衡負載時，當負載分別為500W、1500W時，可見變流器輸出電壓得穩定性，中性線電流恰為兩相電流之差值；圖7.7發生電容電壓不平衡現象，若單純以電壓控制輸出，由圖中可見其輸出電壓雖達穩定，但將會有零點飄移現象，雖平衡負載下，但中性線仍有一直流成分。但經本研究閉迴路控制架構下，其直流準位已能消除。

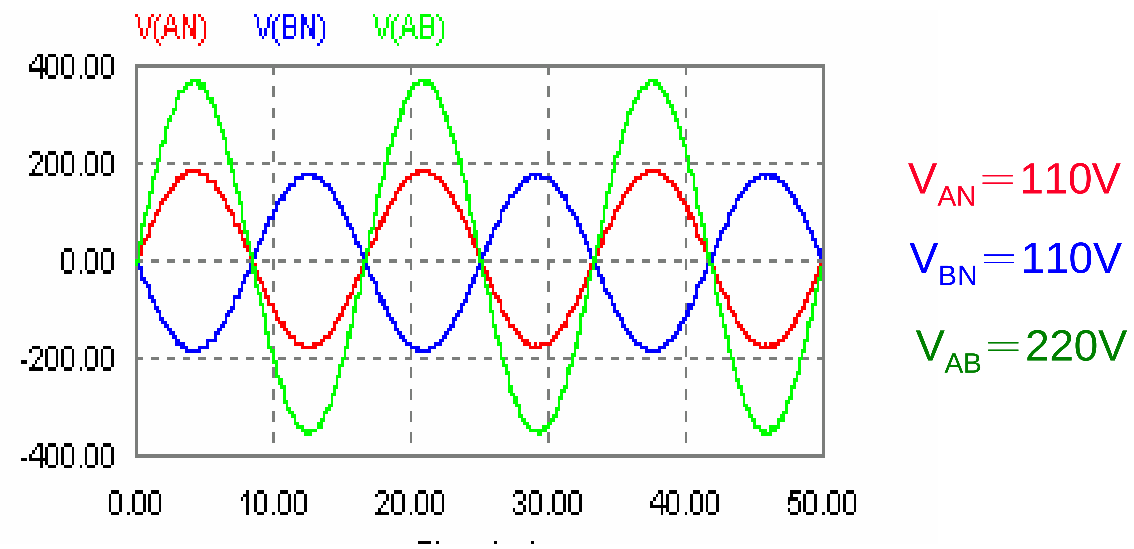


圖 7.5 單相三線制輸出電壓模擬圖

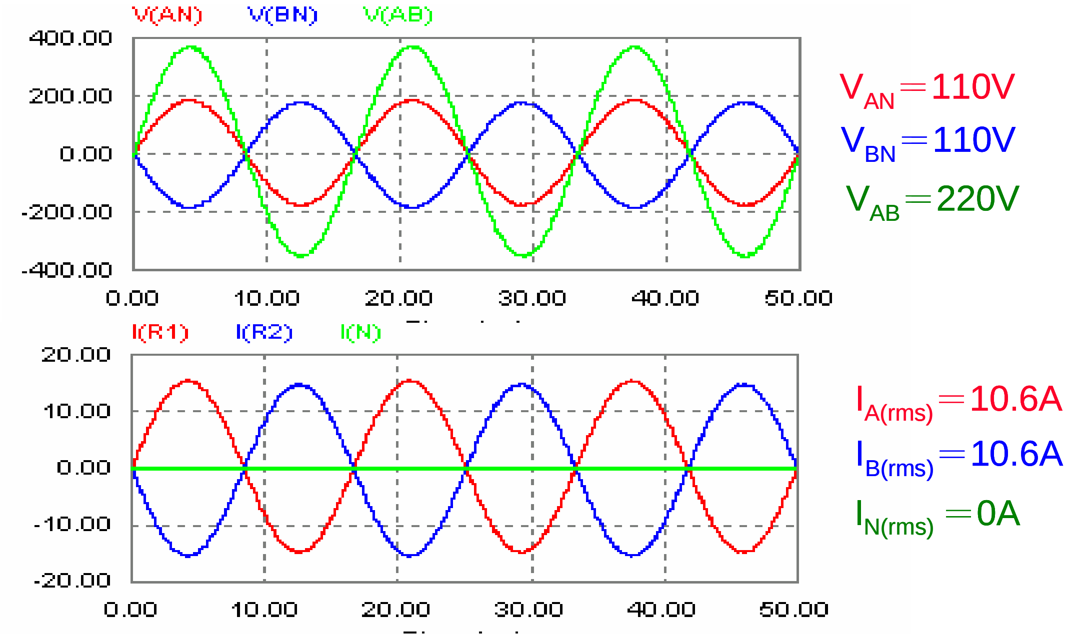


圖 7.6 平衡負載輸出電壓模擬圖

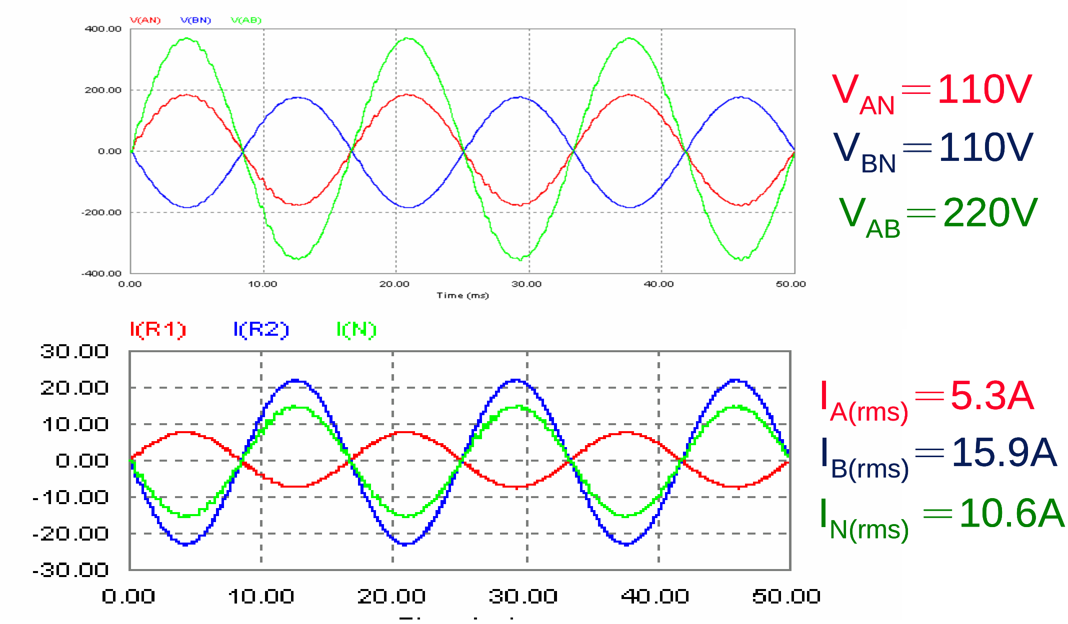


圖 7.7 不平衡負載輸出電壓模擬圖

八、太陽光變頻器之硬體設計與實現

本計畫一方面發展太陽光發電技術，另一方面也研製一個具有商品化潛力的2 kVA併網型太陽光變頻器。圖8.1為本計畫所規劃的多功能併網型太陽光變頻器的功能方塊圖，其中的電池與充電器為附加功能，並未列入本計畫的研究項目，但預先納入設計規劃，做為未來可擴充之附加功能。

圖8.2是所設計太陽光變頻器DSP數位控制器的系統架構圖，針對控制器與功率轉換板間的介面定義了一個共通的Power Bus，簡稱為P-Bus，藉由此P-Bus的定義可將不同型式的功率級與控制器予以整合。圖8.3為DSP數位控制器的功能方塊圖，其中的控制核心為德州儀器公司所製造的單晶片數位信號處理控制器。

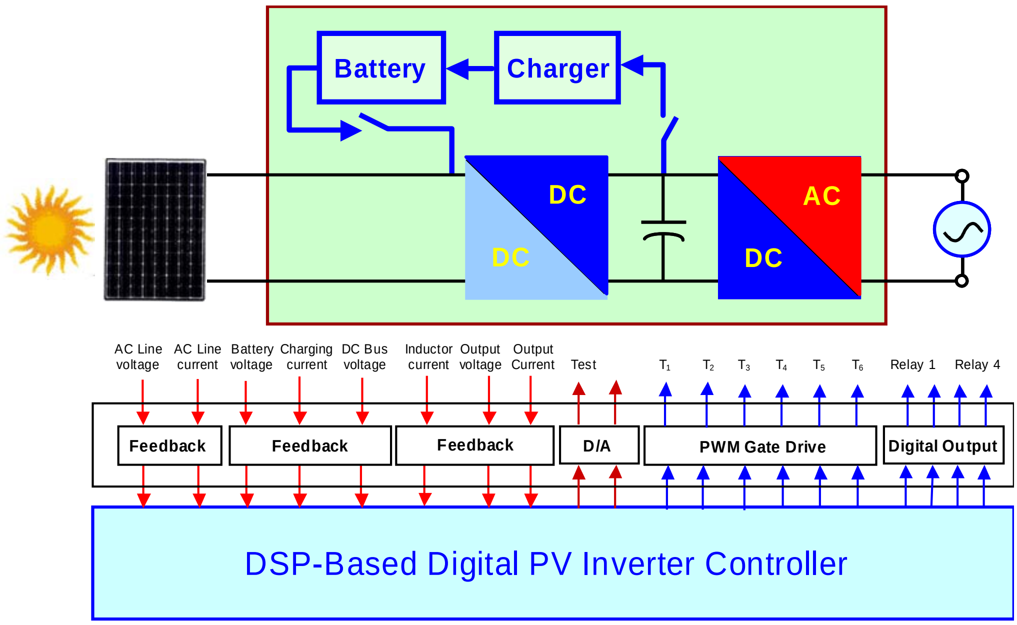


圖 8.2 太陽光變頻器 DSP 數位控制器的系統架構

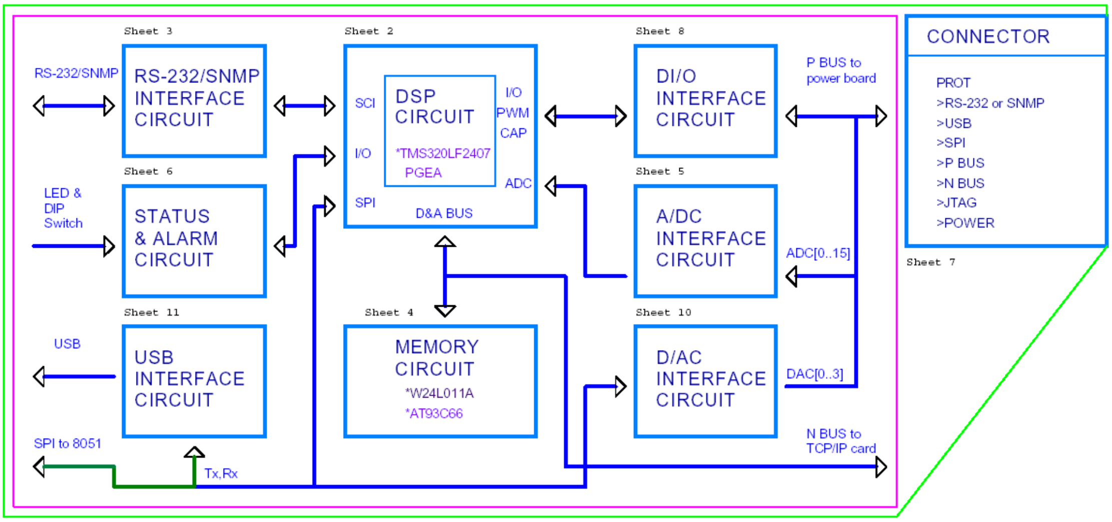


圖 8.3 DSP 數位控制器的功能方塊圖

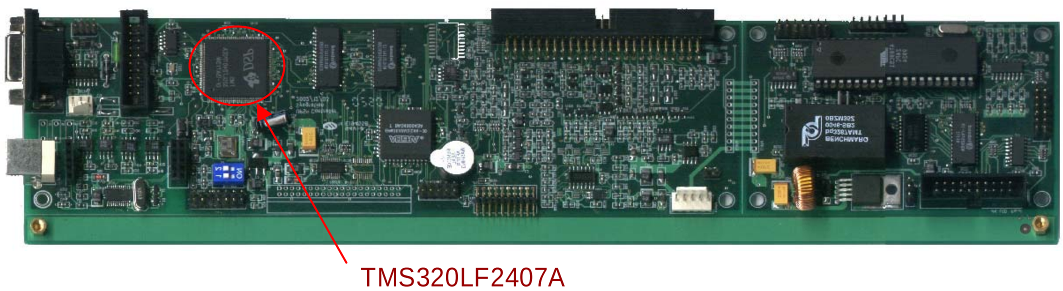


圖 8.4 研製完成的 PV inverter DSP 數位控制器

圖8.4是研製完成的PV inverter DSP數位控制器，採用新型的單晶片DSP控制器TMS324F2407A，工作時脈為40 MHz，指令週期為25 nsec，具有多組可程式PWM產生器與16組多工時脈觸發之可程式ADC轉換頻道，是一顆功能強大且低單價(約320台幣)的單晶片DSP。

圖8.5是研製完成的2kVA PV-Inverter功率電路板，圖8.6是整合測試中的DSP控制併網型太陽光變頻器實驗系統，包括研製完成的DSP控制板以及2 kVA的功率板，未來將以此為基礎繼續發展DSP韌體控制技術與改善太陽光發電的轉換效率。

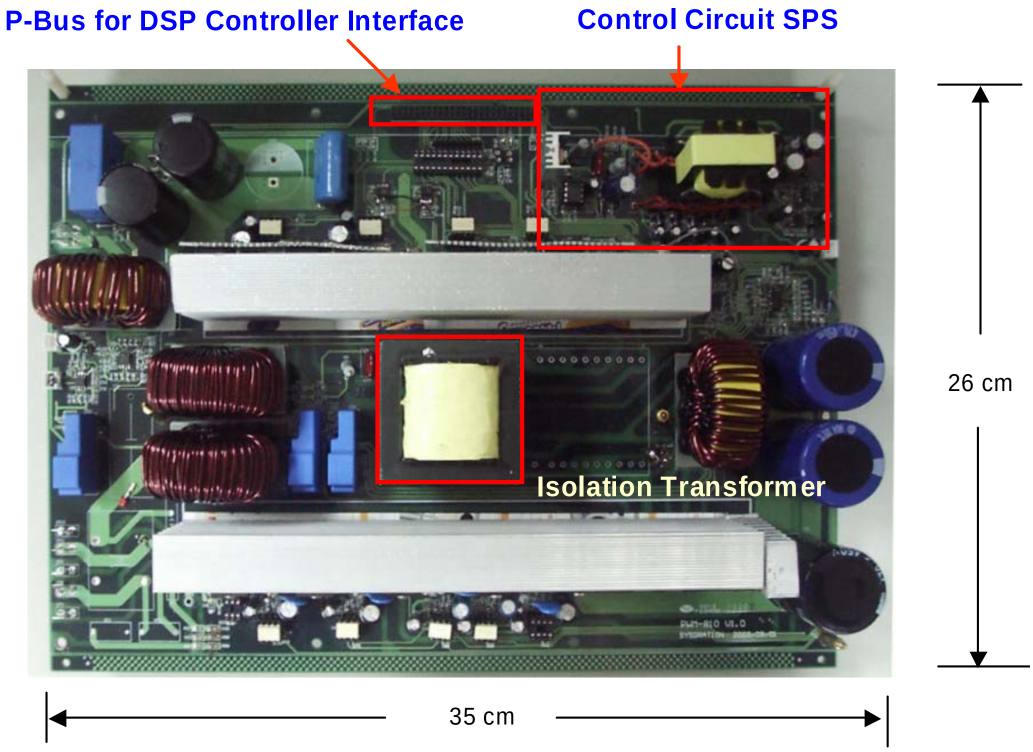


圖 8.5 研製完成的 2kVA PV-Inverter 功率電路板

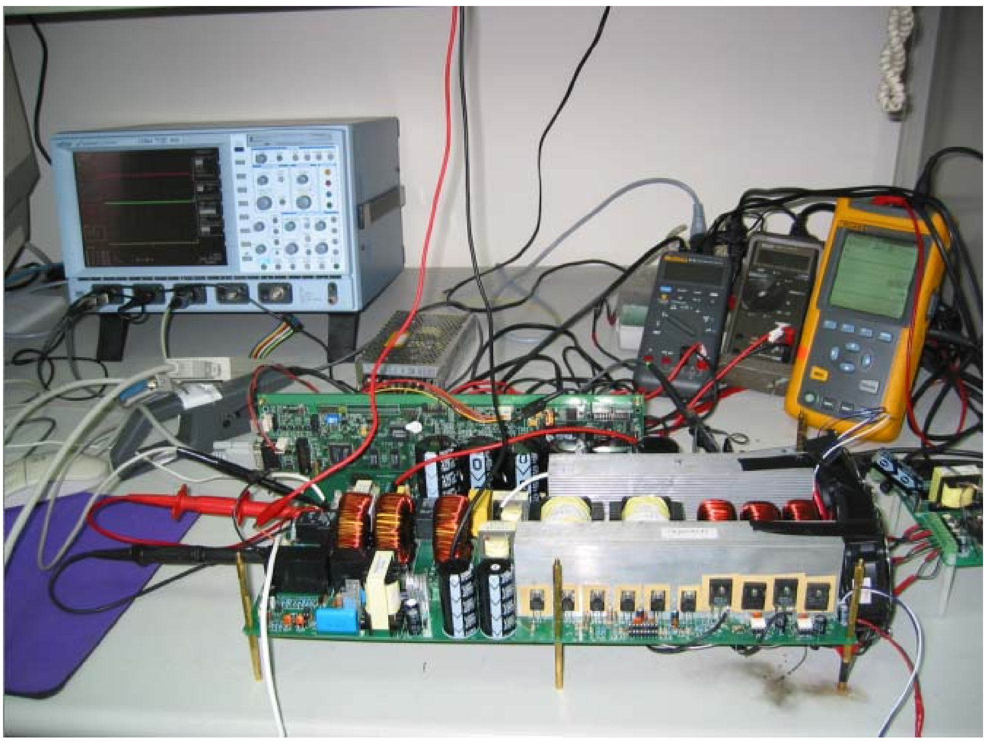


圖 8.6 整合測試中的 DSP 控制併網型太陽光變頻器

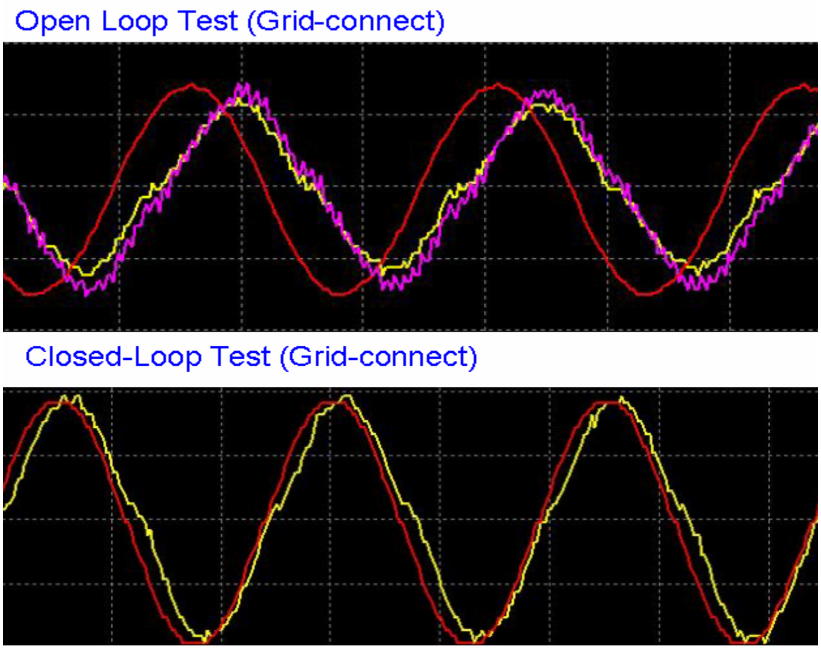


圖 8.7 併網模式輸出功率 2kW 的實驗結果

併網型太陽光變頻器必須具備市電同步輸出電流調節控制、最大功率追蹤控制、孤島效應保護、以及獨立運轉交流穩壓等功能，為了達到這些功能並且提高整體運轉效率，使太陽光變頻器在不同供電狀況均能保持良好的供電品質與穩定性，必須具備良好的控制與整合。本計畫發展完成『太陽光變頻器DSP全數位控制技術』，可應用於電力電子產業、再生能源產業、綠色能源等產業，發展如併網型太陽光變頻器、獨立型太陽光變頻器、複合型太陽光變頻器、燃料電池變頻器、交流電源穩壓器、電池充電器等產品。

圖8.6是本計畫所建立DSP控制併網型太陽光變頻器實驗系統，包括研製完成的DSP控制板以及2 kVA的功率板，圖8.7是在110V、60 Hz併網操作模式輸出功率2kW的實驗結果。未來將以此為基礎繼續發展孤島效應偵測方法、DSP韌體控制技術、與改善併網變頻器的整體效率。

九、研究成果與討論

本階段之研究已設計完成一個以單晶片DSP控制器為基礎的全數位隔離式雙級單相併網型太陽能光伏變流器。本計畫所發展的併網變流器，具有電路簡單、效率高、符合市電併聯需求與快速動態響應的特色。採用全數位式設計達到光伏能之高轉換效率、最大功率追蹤及市電併聯技術及保護等多項複雜之快速控制需求，採用多迴路控制方式，回授調整追蹤太陽能板之最大輸出能量，提供穩定之直流鏈電壓；後級則控制兩組半橋式轉換器輸出提供共地點，適合市電併聯需求以發展併聯技術。

本技術發展以單晶片DSP為核心的併網型太陽光變頻器軟體控制技術，採用TMS320F2407A單晶片DSP控制器，經由規劃的系統介面，發展模組化的DSP控制程式。本技術內容包含：DSP單板控制器、即時韌體介面模組程式、以及強韌型電流調節控制程式。

併網型太陽光變頻器必須具備市電同步輸出電流調節控制、最大功率追蹤控制、孤島效應保護、以及獨立運轉交流穩壓等功能，為了達到這些功能並且提高整體運轉效率，使太陽光變頻器在不同供電狀況均能保持良好的供電品質與穩定性，必須具備良好的控制與整合。本計畫發展完成『太陽光變頻器DSP全數位控制技術』，可應用於電力電子產業、再生能源產業、綠色能源等產業，發展如併網型太陽光變頻器、獨立型太陽光變頻器、複合型太陽光變頻器、燃料電池變頻器、交流電源穩壓器、電池充電器等產品。

本計畫發展以單晶片DSP為核心的併網型太陽光變頻器軟體控制技術，採用TMS320F2407A單晶片DSP控制器，經由規劃的系統介面，發展模組化的DSP控制程式。本技術內容包含：DSP單板控制器、即時韌體介面模組程式、以及強韌型電流調節控制程式。本文發展的數位式最大功率追蹤控制，擁有寬廣的電壓輸入範圍及高效率轉換，適用於偏遠地區無人操控之

監測及通訊站等多項機動性之電源解決方式，並可做為未來發展高效能環保發電的預備工作。

本計畫所發展的PV inverter控制技術有如併網型太陽光變頻器的控制引擎(control engine)，發展以先進DSP為核心的電源轉換器韌體控制技術，針對併網型太陽光變頻器發展了特殊功能的控制模組。本技術可結合不同電路架構的功率級發展成為具有特色的單相併網型變頻器，可大幅節省系統廠商開發併網型太陽光變頻器的時間與金錢。

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計畫成果自評：

本計畫發展併網型太陽光變頻器的核心數位控制技術，所發展之技術有如併網型太陽光變頻器的控制引擎(control engine)，採用先進單晶片DSP為控制核心，具有低價格(單價約10美金)、高性能(40 MIPS)的優點，發展以先進DSP為核心的電源轉換器韌體控制技術，針對併網型太陽光變頻器發展了特殊功能的控制模組。本技術可結合不同電路架構的功率級發展成為具有特色的單相併網型變頻器，可大幅節省系統廠商開發併網型太陽光變頻器的時間與金錢。

本計畫研製完成一個以單晶片DSP控制器為基礎的全數位隔離式雙級單相併網型光伏變頻器，具有電路簡單、效率高、符合市電併聯需求與快速動態響應的特色。適用於110V、60Hz，額定功率為2kW，最高功率轉換效率達94%，額定輸出電流總諧波失真為3.5%，技術特點簡述如下：

- 單晶片 DSP 全數位控制技術
- 110V、60Hz，額定功率為 2kW
- 單級最高功率轉換效率達 94%
- 低諧波失真同步電流取樣控制技術
- 功率回授式最大功率工作點追蹤方法

附錄

- Alan Wang, Bruce Chen, and Ying-Yu Tzou, “Development of high-frequency transformer inverter topologies for small-power grid-connected PV inverters,” Solar World 2005.
- Kuo-Lung Chai, Yue-Chun Lin, Jing-Fong Hsu, and Ying-Yu Tzou, “Review of PV inverter technologies for practical implementation,” Solar World 2005.

DEVELOPMENT OF HIGH-FREQUENCY TRANSFORMER INVERTER TOPOLOGIES FOR SMALL-POWER GRID-CONNECTED PV INVERTERS

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ABSTRACT

This paper presents a review of the state-of-the-art development of small-power grid-connected inverter topologies for practical implementation. Unique requirements for small distributed power generation systems include low cost, high efficiency and tolerance for an extremely wide range of input voltage variations. Selection guide lines are given based on application requirements and cost considerations. Special attentions are focused on the analysis of switch utilization factor in comparing competitive inverter topologies.

Keywords — Photovoltaic inverter, grid-connected inverters, inverter topology, distributed power generation.

1. INTRODUCTION

Due to the forthcoming energy crisis and global environment protection, exploring renewable energy for distributed power generation has become a world wide research issue [1]. Among various approaches in exploring renewable energy, economic conversion of solar and wind energy into utility power has gained much attention due to their continuing improvement in cost per Watts, reliability, and easy installation. Small-power PV and wind power generation are moving from being mainly an R&D activity during 1990s to being one that needs promotion in the market since 2000s and will become a major market thrust for power generation after 2010s [2]. During the development and promotion of PV inverters one major goal is the need to develop cost reduction techniques to be competitive with conventional power generation techniques.

Basically, the PV inverter system can be classified as either stand-alone or grid-connected (or line tied). Sometimes, a combination of both functions, a hybrid inverter is adopted. Batteries are usually employed in a stand-alone inverter for electrical energy storage and the inverter provides a regulated ac voltage source to its load independent to the utility. While as, for a grid-connected inverter the batteries are usually not used, and the inverter provides a synchronously regulated ac current source to feed the utility.

The inverters can be designed to control the power flow between these regenerative power sources and loads. When the utility is active, the inverter behaves as a current-regulated inverter to supply current to the load and even to the source. On the other hand, if the utility is inactive, the inverter behaves as a voltage-regulated inverter to supply power to the load. If the inverters are designed to regulate power from PV modules to ac utility they are named grid-connected PV inverters.

2. PV SYSTEM ARCHITECTURE

The PV modules can be series or parallel connected to provide the dc source power for the PV inverters. There are various configurations for the grid-connected PV systems as shown in Fig. 1. Fig. 1(a) shows a centralized PV inverter. The PV modules are organized to provide a specified voltage and current supplying capability. This kind of PV inverter is usually used in large capacity PV plant with a rating greater than 100 kVA. Fig. 1(b) shows a PV plant with string inverters. The PV modules are serially connected to provide a higher dc link voltage for the connected PV inverter. This kind of PV inverter provides advantages of single-stage power conversion with higher efficiency and is suitable for medium power applications.

Several smaller dc-dc converters can be used to convert a lower dc voltage from a string connected PV modules to a central inverter with a higher dc input voltage. This multi-string inverter configuration, as shown in Fig. 1(c), requires only one central inverter for the supervisory and islanding protection functions. These smaller dc-dc converters can be designed with MPPT control function to achieve higher efficiency, modular structure for a lower price, and minimization of losses due to dc transmission loss and mismatch of PV modules.

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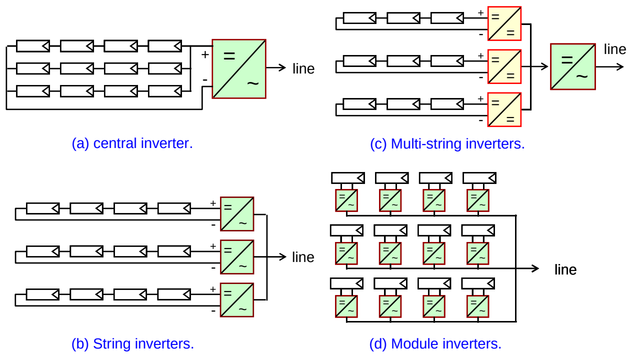


Fig. 1 Architecture of grid-connected PV inverter systems.

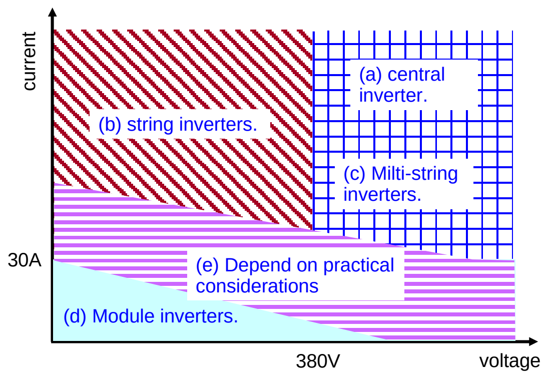


Fig. 2. Classification of grid-connected PV inverter systems according to power ratings.

Module PV inverters, also known as AC module, with rated power typically around 75-400W is shown in Fig. 1(d). Because of the low voltage of the PV module, this kind of inverter usually requires two-stage power conversion and results lower over-all efficiency. However, these module inverters provide highest flexibility and most suitable for low power applications. The applications of these PV plant configurations can be classified according to their power ratings as shown in Fig. 2. There are regions that need to consider practical limitations and economical concerns.

The functions of a grid-connected inverter include dc–ac conversion, output power quality assurance, various protection mechanisms, and system controls. These requirements have driven the inverter development toward simpler topologies and structures, lower component counts, and tighter modular design. Both single-stage and multiple-stage inverters have been developed for power conversion in distributed power generation (DG) systems. The circuit topologies for single-phase PV inverters have been classified according to number of switches, isolated or non-isolated, hard-switching or soft-switching.

3. DEVELOPMENT OF ISOLATED INVERTER TOPOLOGIES

There are various topologies developed for the grid-connected PV inverters [3]-[7]. Selection of a topology plays key step in designing a high-performance grid-connected PV inverter. Efficiency, cost, and controllability are major concerns in determination of the PV inverter topology. This paper discusses this issue.

The small-power module inverters or string inverters, lower than 1 kW, have a great potential to become a standard commercial product for residential power generation. An important goal in developing modern grid-connected inverters for distributed power generation is to reduce its cost per watts lower than 0.25 US$/Watt and a MTFF (meat time of first failure) longer than 10 years. One key factor in the design of modern inverters to meet these stringent design requirements is the development of low cost inverter topologies.

The inherent characteristics for ac-dc and dc-ac power conversion can be explained as illustrated in Fig. 3. The AC power can be converted into dc power only through a nonlinear asymmetrical resistance, e.g., a rectifier. DC power can be converted into ac power only through the action of an active resistive element, i.e., one containing a region of negative slope [8]. Realization of a dc-ac inverter requires the differential connection of two dc-dc converters as shown in Fig. 4. Basic dc-dc converters, such as buck, boost, and buck-boost converters, or other derived dc-dc converters, such as Cuk or SEPIC converters can be used to synthesize various inverter topologies. The derived inverter can be further isolated from its output by employing either a high-frequency transformer in the intermediate stage or a line frequency transformer in its output. Because the inverter possesses an inherent four-quadrant operation characteristics it can be used for bidirectional power flow control in during the energy conversion process.

The topologies of grid-connected inverters can be classified as two major categories: transformer and transformerless. A transformer PV inverter can provide isolation and larger voltage regulation range with the cost of adding a power transformer. In a PV inverter with line frequency transformer, the power devices are switched at line frequency with minimum switching losses while this low frequency results a bulky transformer. This line-frequency transformer can be replaced with a high-frequency transformer by using high-frequency power conversion techniques. In an inverter with high-frequency transformer, a dc-ac inverter switching at high frequency is required to reduce the size of the power transformer. However, the increase of the switching frequency must make a compromise with the additional switching losses and stresses.

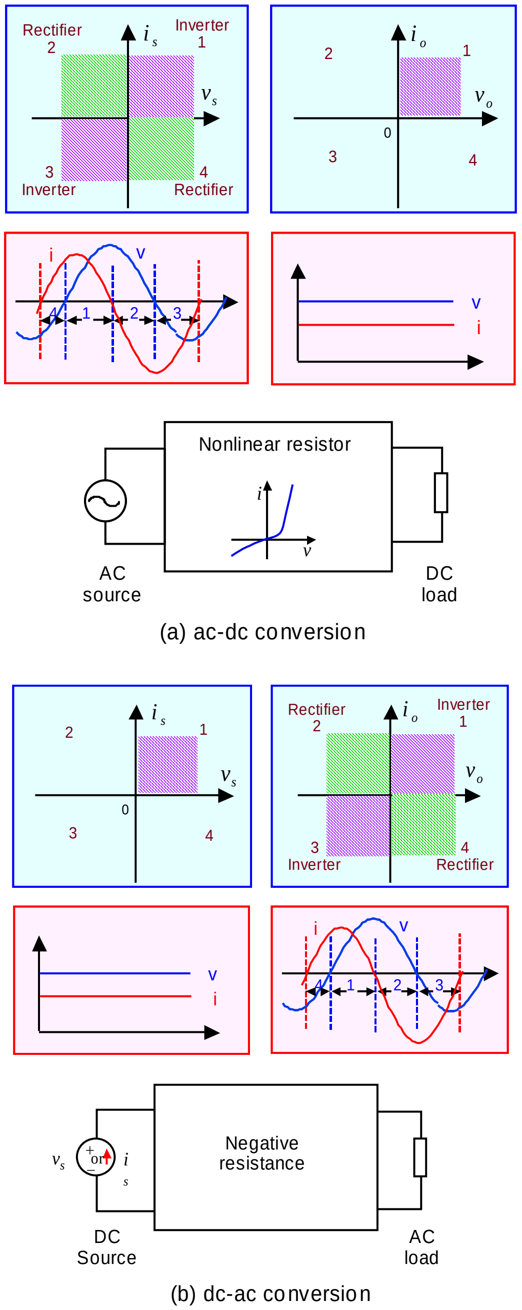


Fig. 3. Characteristics of ac-dc and dc-ac power conversion.

Fig. 5(a) shows a nonisolated four-switch buck-boost inverter with a single input dc source [9]. This inverter consists of two differentially connected buck-boost dc-dc converters. The output ac voltage can be either higher or lower than its dc input. This converter suffers high current switching stress in its input transistor pairs when the input dc voltage is low. Fig. 5(b) shows its isolated version by using an intermediate high-frequency transformer [10].

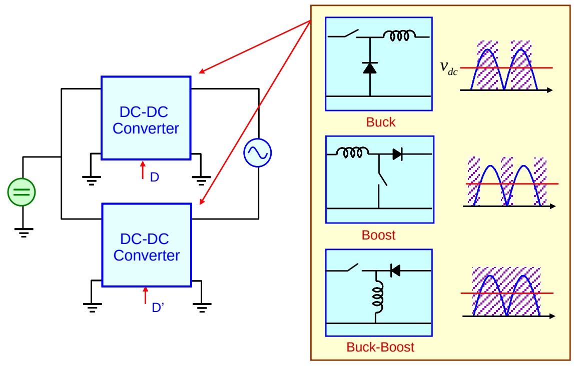


Fig. 4. Derivation of inverter using differential-connected buck, boos, and buck-boost converters with a single dc voltage source.

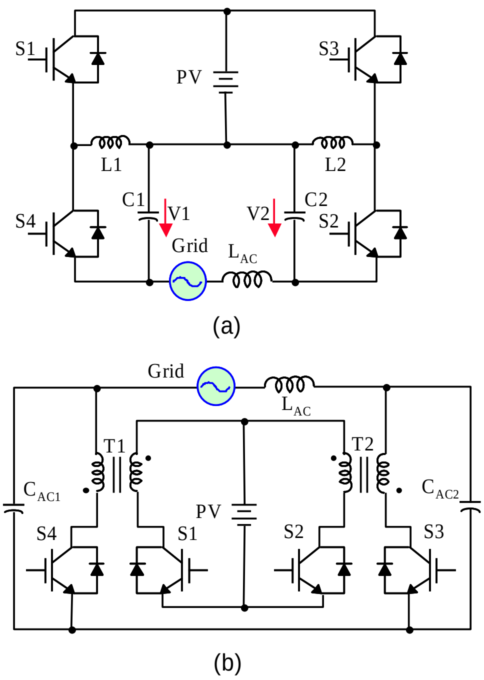


Fig. 5. Differentially-connected four-switch buck-boost inverter with single input dc source (a) nonisolated and (b) isolated.

Fig. 6 shows an isolated six-switch flyback buck-boost inverter with a single input dc source [11]. The two additional switches in the output stage are used for synchronous commutation during each half cycle of its ac output. Reverse power flow is not possible in this converter. The flyback transformer limits this inverter in low power applications. The leakage inductance of the Flyback transformer also imposes high voltage switching stresses to the switching devices. This inverter has advantages of using commonly used components in off-line switching power supplies and is suitable for applications in low-power AC modules.

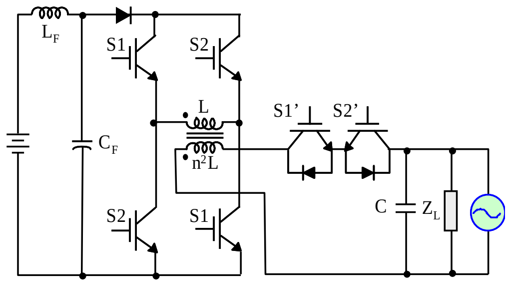


Fig. 6. Six-switch isolated buck-boost inverter by Nagao and Harada [11].

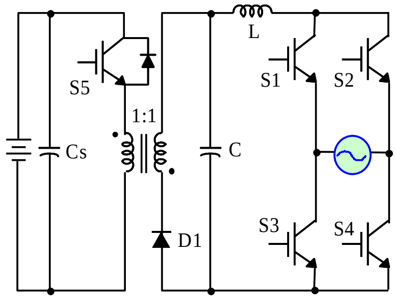


Fig. 7. Two-stage isolated buck-boost inverter by Saha and Sundarsigh [12].

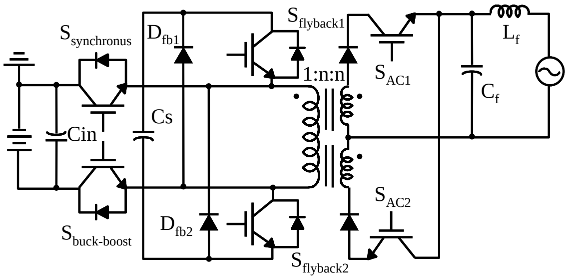


Fig. 8. Flyback inverter with enhanced power decoupling capability by Shimizu [13] and Kjaer [14].

To enhance the input voltage control range of an inverter, multi-stage converter can be adopted. Fig. 7 shows a two-stage isolated buck-boost inverter proposed by Saha and Sundarsigh [12]. The primary switch S5 in the front-state is switched at high frequency to reduce the size of the transformer and the four switches in the output stage switching at low frequency to reduce the switching stresses. Fig. 8 shows a flyback inverter with enhanced power decoupling capability by Shimizu [13] and Kjaer [14]. This inverter topology has advantage of using a small-size intermediate dc capacitor for energy storage. Fig. 9 shows a bidirectional dc-ac inverter by Beristáin et al. [15]. Thos converter has a merit that no additional DC-link stages are required, providing a reduction of components.

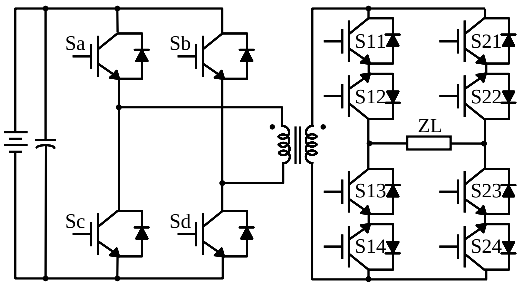
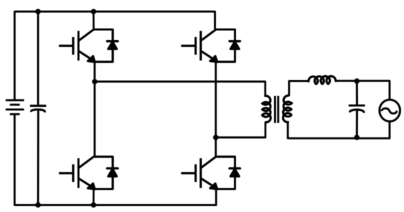
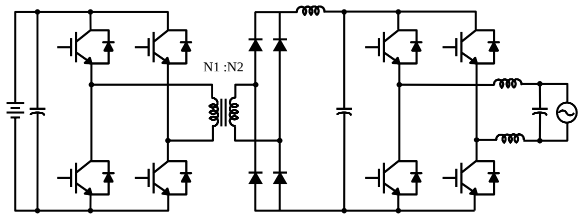


Fig. 9. Bidirectional dc-ac- inverter by Beristáin et al. [15].



(a)



(b)

Fig. 10. (a) Single-stage full-bridge isolated inverter, and (b) double-stage full-bridge isolated inverter.

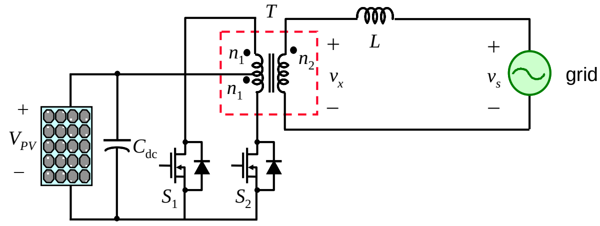


Fig. 11. Push-pull inverter topology

Fig. 10(a) shows a voltage source single-stage full-bridge PWM inverter switching at high frequency for sinusoidal current fed control and Fig. 10(b) is a two-stage high-frequency transformer Inverter. Fig. 11 shows the push-pull inverter topology and Fig. 12 shows the half-bridge inverter topology. High-frequency output transformers are employed in these inverters for grid coupling and isolation. Leakage inductances can be utilized to reduce the size of the output inductor. A synchronously commutated bidirectional switch can be added to the output to prevent reverse power flow.

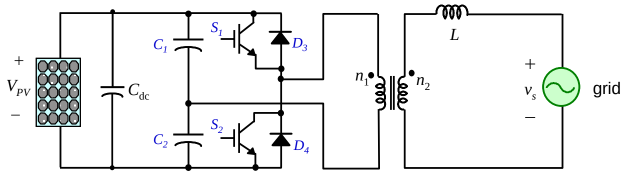


Fig. 12. Half-bridge inverter topology.

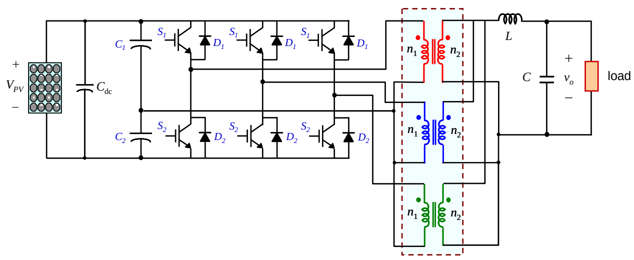


Fig. 13. Multiphase half-bridge inverter topology.

Fig. 13 shows a multiphase half-bridge inverter topology. Several synchronously controlled half-bridge inverters can be integrated together with phase-shift PWM control scheme to reduce the size of the output filter inductor. This inverter topology has advantages of employing integrated magnetic components for modular design and manufacturing of low-cost high power density converters in applications to PV AC modules.

4. CONCLUSION

This paper has made a review of the development of the converter topologies for isolated grid-connected PV inverters. The design and application considerations in determination of the PV plant configuration and PV inverter topology have been given. The employment of high-frequency transformer in the design of a grid-connected PV inverter gets its highest benefits in low-power low-voltage applications. With the increase of power ratings, the design of high-frequency transformer becomes another challenging design issue. For low-power grid-connected PV inverter in applications below 1 kW, the high-frequency transformer isolated inverter with single-stage conversion will become most widely adopted inverter topology. Additional research works are needed for a further study in design and evaluation of these high-frequency isolated inverter topologies in applications to small distributed power generation systems.

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REVIEW OF PV INVERTER TECHNOLOGIES FOR PRACTICAL IMPLEMENTATION

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ABSTRACT

This paper report presents a review of the state-of-the-art development of single-phase photovoltaic inverters. We focus on technologies for the performance improvement and cost reduction techniques developed for the design of small power lie tie PV inverters. Some practical design considerations are given for a DSP-controlled PV inverter. An integration of the-state-of-art PV inverter control techniques has been developed for a single-chip DSP-controlled grid-connected PV inverter with a rating of 2kW. Experimental results of the designed inverter show a high energy-efficiency of 94 % and a low distortion on the line current with a current THD of 2.4% at rated power.

1. INTRODUCTION

PV power generation, which directly converts solar radiation into electricity, has many advantages such as pollution-free, silent, and inexhaustible. With increasing applications of solar photovoltaic devices, various solar-powered apparatuses have been devised. PV power generation is moving from being mainly an R&D activity during 1990s to being one that needs promotion in the market since 2000s [1]. One major goal is the need to develop cost reduction techniques to be competitive with conventional power generation techniques. However, the development of modern PV inverters is still a state-of-the-art synergy technology. One major design challenge is to make a compromise between its cost and efficiency [2]-[4].

The efficiency is defined based on how many Watt-hours generated based on a constant insolation. There are many consideration factors involved in the design of a practical PV inverter. These may include inverter topology selection, maximum power point tracking (MPPT) algorithm, inverter control technique, and islanding detection algorithm in large, and power device switching technique, PWM modulation algorithm, current sensing technique, control loop design, EMC design in details. There exits both theoretical issues for optimal performance and practical realization issues for cost reduction.

This paper focuses on the investigation of technologies for the performance improvement and cost reduction techniques developed for the design of small power lie tie PV inverters. We make a review of recent development of photovoltaic inverter technologies. The scope of this review is focused on PV inverter circuit topologies, line current control techniques, maximum-point power tracking techniques, and islanding detection schemes. The development of grid-connected PV inverters are summarized by the demonstration of a designed DSP-controlled 2kW PV inverter.

This paper is organized as follows. Sec. 1 makes a brief introduction of PV inverters for renewable energy generation. Sec. 2 introduces the development of inverter topologies, Sec. 3 makes a review of the MPPT algorithms, and Sec. 4 presents digital control techniques for the synchronized inverter current control. Sec. 5 introduces the development of islanding algorithms for grid-connected inverters for distributed power generation. Sec. 6 presents the development of a low-cost high-efficiency DSP-controlled 2kW PV inverter for distributed power generation. Sec. 7 is the conclusion.

2. INVERTER TOPOLOGIES

There are various topologies developed for the grid-connected PV inverters [5]. Selection of a suitable topology is a key step in designing a high-performance grid-connected PV inverters. Efficiency, cost, and controllability are major concerns in determination of the PV inverter topology.

The topologies of grid-connected PV inverters can be classified according to whether it is transformer or transformerless, one-stage or two-stage, hard-switched or soft-switched, etc. A transformer PV inverter can provide isolation and larger voltage regulation range with the cost of adding a power transformer.

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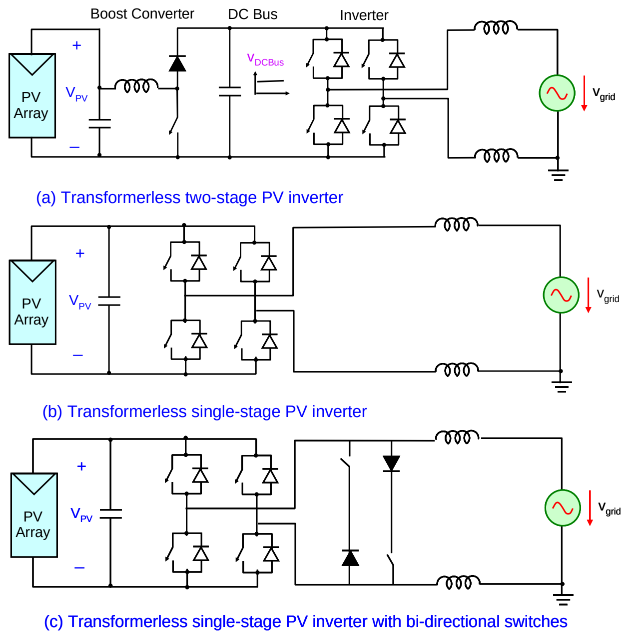


Fig. 1. Transformerless PV inverter topologies.

Fig. 1 shows major transformerless PV inverter topologies for small power distributed generation, they may use two-stage or single-stage; single-level or multi-level for power conversion. Single-stage transformerless inverter has advantages of simple circuit topology, low cost, and high efficiency, but with the demerits of limited voltage conversion range.

Multilevel converter technology is based on the synthesis of the AC voltage from several different dc voltage levels. Multilevel converters are well recognized in applications to high power, medium voltage power conversion. By using several levels of DC voltages, stepped voltages can be generated at low switching frequencies. With the increasing of dc levels, filters can be avoided or filter effort is significantly reduced, the cost is increasing complexity in gating signals generation. However, with the development trend of faster price reduction in active power semiconductor devices compared to passive power devices, multilevel converters can be competitive for low power applications.

Different multilevel topologies are compared in [5] regarding their suitability for a low power, transformerless, single phase, grid connected, photovoltaic (PV) system. Fig. 2 shows a transformerless cascaded 5-level PV inverter [6]. However, the complexity in PWM signals generation for this multi-level converter and possible imbalance of the dc sources make the control a challenging task.

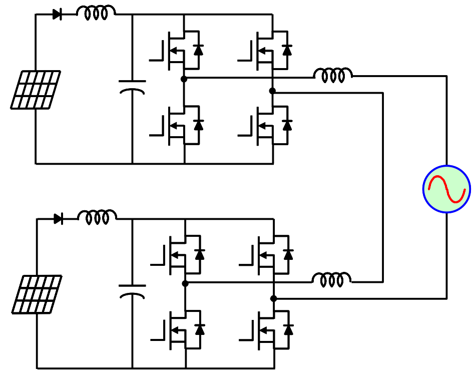


Fig. 2. Transformerless cascaded five-level PV inverter topologies.

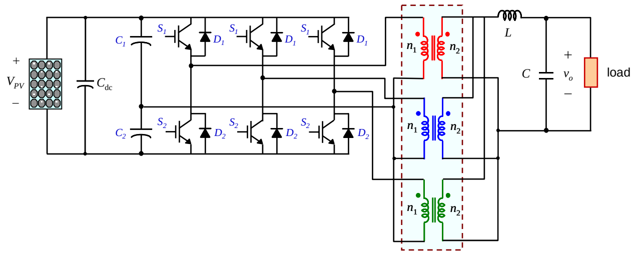


Fig. 3. Multiphase half-bridge converter in applications for single-phase PV inverter.

The transformer-included inverters may either utilize a low-frequency or a high-frequency transformer. The low-frequency transformer has drawbacks of size, weight, and price. Modern inverters tend to use a high frequency transformer. This results in entire new designs, such as the Printed Circuit Board (PCB) integrated magnetic components. High-frequency transformer isolated inverter has advantage of wider input voltage range compared with single-stage transformerless inverter.

Fig. 3 shows the topology of a multiphase half-bridge inverter. This topology has advantages of modular structure, transformer isolated, and small output filter by using phase-shift PWM technique. However, transformer isolation to prevent dc current injected into the grid is not a must during the phase of task V of International Energy Agency-PhotoVoltaic Power Systems (IEA-PVPS) [7], it states that a small amount of injected DC current to the grid does not affect the local distribution transformers.

Various single-stage and multiple-stage single-phase inverter topologies appropriate for small distributed power generation systems have been reviewed and evaluated in [8]. However, ideal inverter topology for small power distribution systems is still to be developed. To improve system reliability and reduce maintenance cost, small transformerless ac modules can be used to compose a multilevel inverter system in accommodation to wide input voltage variations and flexibility for different power rating requirement.

3. MPPT CONTROL TECHNIQUES

The electric power generated by a solar array fluctuates depending on the solar radiation value and temperature. Inverters for PV-applications have to contain MPPT to maintain an optimal power conversion. The conversion of the low voltage generated at the MPP (typically around 17 V for a 36 cells module and 34 V for a 72 cells module) to a corresponding AC current injected into the grid, must be accomplished with the highest possible efficiency and fast dynamic response over a wide range of PV-power. This requirement is dependent on the irradiation distribution of the sun and characteristics of the solar cells. A practical PV inverter is required to develop MPPT control scheme to track the maximum output power operating point irrespective of the operating conditions of insolation and environment temperature.

Various methods of maximum power tracking have been considered in photovoltaic power applications [9]–[10]. All these methods based on searching the maximum power point either by a perturbation of the operating point, calculation of the solar impedance, or searching for a maximum power generation. The "perturb and observe (P&O)" algorithm detects the change in the solar array output power by continuously changing the operating point of the PV array. The P&O algorithm is simple and easy for implementation, however, it also has drawbacks of slow response to discontinuous changes of insolation.

To improve this drawback, an incremental conductance algorithm (IncCond) based on the fact that the array terminal voltage can always be adjusted towards the Vmax value by comparing the incremental and the instantaneous conductances of the PV array. The IncCond method needs to calculate the harmonic components of the array voltage and current to adjust the array reference voltage, which requires to develop fast and reliable method to identify the incremental conductance of the solar array. In [11], the P&O method was implemented using in a DSP with a self-tuning function, which automatically adjusts the array reference voltage and voltage step size to achieve the maximum power tracking under rapidly changing conditions.

A PV model based on the Shockley diode equation has been developed in [12] by using MATLAB and is used for the evaluation of different converter topologies for MPPT control. This model can be used to investigate the variation of maximum power point with temperature and insolation levels. Reference [10] has made a comparison between fixed voltage and self-adapting MPPT for low power PV inverters and it is found that the difference between the various strategies is small. However, with the development of low-cost high-performance microcontroller and dedicated PV inverter microcontroller, MPPT control is a required function for PV inverters. Special design must be carried out during low insolation condition. A limit cycle may occur in the V-I plane when the power-voltage curve becomes top flatted during low insolation. Combination of different MPPT methods can be used to solve this problem. In consideration of the performance and realization of the surveyed MPPT algorithms, a power equilibrium searching algorithm combined with fuzzy identification of solar array conductance has been adopted for the realization of a DSP-controlled grid-connected two-stage PV inverter.

4. CONTROL TECHNIQUES

A stand-alone PV inverter needs to provide regulated sinusoidal output voltage with low voltage THD for any possible connected loads. A grid-connected PV inverter needs to feed in-phase current to the grid with low current THD under large input power variations. In either case, high-quality control of the inverter output current or/and voltage is required.

When an inverter is connected to the grid, the power quality and the dynamic performance are affected by the line filter connected between the converter and the grid, and by nonlinearities caused by the inverter. For a grid-connected inverter for distributed power generation, it is also required to have low THD of the inverter output current, in phase with the line voltage, and low dc current, smaller than 0.5A for transformerless inverters. The unit power factor control can be achieved by using a high switching frequency inverter with instantaneous feedback control. The current control loop can be either implemented by using analog or digital techniques. Although the analog control scheme is simple and easy to realize, it has demerits of not easy for the integration with other PV inverter functions, requiring higher switching frequency than necessary, limited flexibility, and only feasible for simple converter topologies. On the other hand, digital control offers potential advantages of lower sensitivity to parameter variations, programmability and possibilities to improve performance using more advanced control schemes.

During the past years, various digital control schemes have been developed for the current and voltage regulation of voltage source PWM inverters. Reference [13] has made a review and comparison of different state feedback decoupling control topologies applied to inverters for voltage regulation. The dynamic stiffness, an inverse of the output impedance, has been adopted in evaluation of the inverter control performances. It has concluded that a low-cost filter capacitor current feedback controller exhibits very good stiffness to nonlinear load changes and a 0.5% voltage THD measured at rated rectifier load has been obtained.

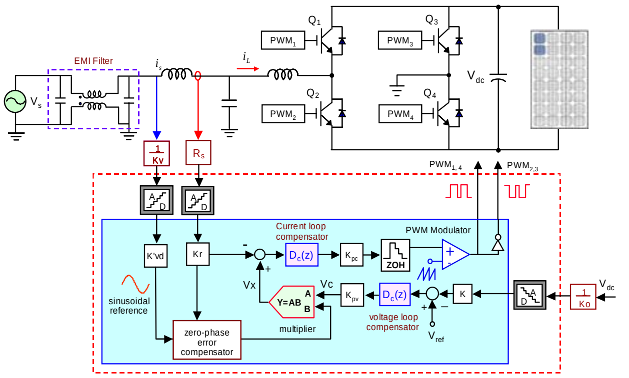


Fig. 4. Digital line current control of a grid-connected inverter for unit power factor.

The voltage-source current-regulated inverter for distributed power generation needs to feed sinusoidal current in phase with the grid voltage with low total harmonic distortion. Fig. 4 shows the block diagram of a grid-connected PV inverter using digital current control technique. A second-order T-type filter is used to smooth the output current. The output current and grid voltage are sensed for the current regulation in synchronous with the grid voltage. The dc-link voltage is regulated to maintain at a constant value for power balance control. Digital control techniques provide flexibility for the implementation of sophisticated PWM generation scheme for low-order harmonic control. Digital control techniques can used to improve the converter efficiency by a reduction of the switching frequency. These new control methods may lead to the development of a PV inverter to achieve a specified power factor with a lower switching frequency.

5. ISLANDING DETECTION TECHNIQUES

A fault occurring in the power distribution system is generally cleared by the protective relay that is located closest to the faulty spot. As a result, a distributed generation system (DG) tries to supply its power to part of the distribution system that has been separated from the utility's power system. In usually conditions, this DG assumes an overloaded condition, where its voltage and frequency are lowered and it is finally led to stoppage. However, though this is a rare case, a DG (or a group of generators) connected to this islanded system may provide with a capacity that is large enough to feed power to all the loads accommodated in the islanded system. When the loads are fed power only from the DG even after the power supply is suspended from the power company, such a situation is called an "islanded operation" or "islanding" [14].

Fig. 5 shows the block diagram of an inverter side islanding prevention mechanism. Many methods for the islanding protection have been proposed [15]. These

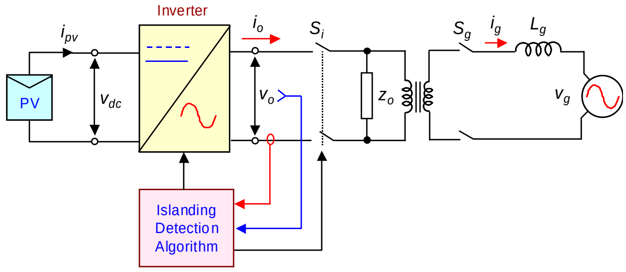


Fig. 5. Inverter side islanding prevention mechanism.

techniques can be classified into two categories: passive and active methods. The passive schemes monitor variations of voltage, frequency, phase, reactive power, harmonic contents, etc. to decide an occurrence of the islanding operation. The active schemes monitor variations of characteristics of the grid by using a perturbation of the injected line current. The status of islanded operation can be detected even under the perfect equilibrium state. Active islanding detection scheme is the major approach in the design of an anti-islanding inverter.

The non-detection zone (NDZ) is the range of local loads for which the islanding prevention method under consideration can be made to fail to detect islanding. The (NDZ) can be used to evaluate the performance of an islanding detection method. Active islanding detection schemes with characteristics of minimum NDZ and easy to implement are major concerns in selection of an islanding scheme.

The Sandia's active islanding algorithm consists of the Sandia frequency shift (SFS) and the Sandia voltage shift (SVS) schemes [16]. The principle of both the methods is an accelerated frequency and voltage drift created with positive feedback to unstabilize the inverter when loose of the utility. In the presence of the utility, the frequency and voltage shifts are not effective in drifting the two parameters. However, once the grid is disconnected, these methods force the frequency and/or voltage to shift outside the operating windows, causing the inverter to disconnect due to o/u voltage and frequency protection. This method may become a standard method in prevention islanding.

6. IMPLEMENTATION OF A PV INVERTER

The development of microelectronics has made low-cost high-performance single-chip digital signal processor (DSP) controller a feasible solution for complicated control functions required in modern motor drives and power electronics. Applying DSP control technique instead of using the conventional analog discrete PWM control ICs, one primary advantage is achieved by replacing hardware with flexible software.

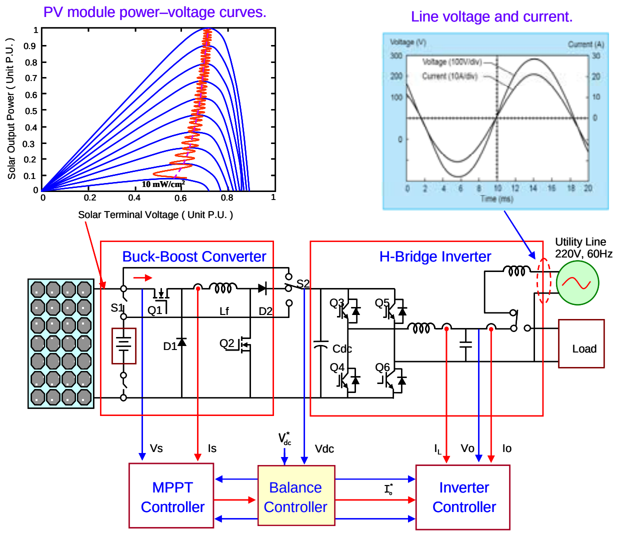


Fig. 6. Integrated control of a two-stage grid-connected PV inverter.

In general, the size of the inverter is dominated by its output LC filter and heatsinks. We can reduce the filter size by increasing the switching frequency; however, this increases overall losses and requires bigger heatsinks with more cooling. Sophisticated digital current and PWM control techniques using advanced fixed-point DSP enables possibility to reduce the size of a dc-ac inverter, increase efficiency, and improve the total harmonic distortion (THD). The synchronous sampling of the inductor current with high current ripples can get a much more accurate and faster current measurement with lower sampling and switching frequency compared with conventional analog current control techniques.

Fig. 6 shows the proposed integrated control scheme for a two-stage grid-connected PV inverter. The front power stage is a buck-boost converter and takes charge in the MPPT control; the rear power stage is a full-bridge converter takes charge in line-fed current control. A balance controller is used for the integration of MPPT and current control. The dc-link voltage is controlled at a specified voltage level according the in-coming solar power.

Fig. 7 shows the block diagram of two-stage grid-connected PV inverter. A fuzzy MPPT control algorithm is developed for the maximum tracking of the solar energy conversion. The algorithm employs heuristic search for maximum power point based on current perturbation of the PV module output current.

In order to reduce the harmonic contents of the inverter output current cascaded output filter and EMI filter are usually used. However, these capacitors will also introduce low frequency dynamics which may instabilize the current control loop or add extra phase lag to its output current. A

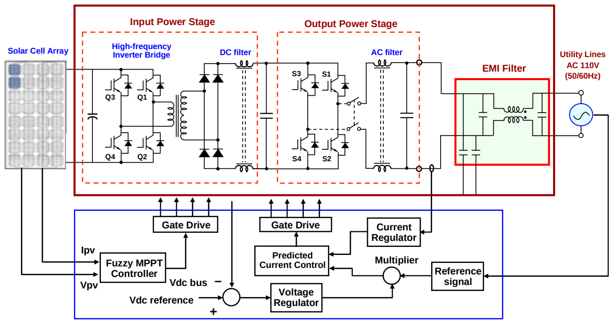


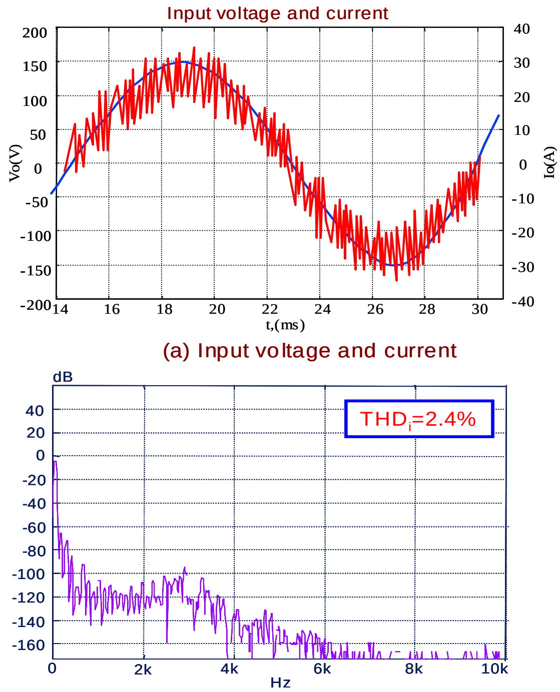
Fig. 7. Block diagram of the designed two-stage grid-connected PV inverter.

Fig. 8. Photographs of the PV inverter under development.

digital zero-phase error compensator is included in the voltage control loop to compensate phase error resulted by the output power filter and EMI filter. Predictive deadbeat current control scheme with synchronous sampling technique is employed for the current loop control.

The practical implementation of the digital inverter controller requires careful considerations in signal sampling and scaling of the feedback signals. Being an inherently wide-band controller, with a very quick speed of response, the controller is very sensitive to feedback noise and disturbances. For this reason, particular care must be taken in the controller PCB layout for low-level signal sampling and ADC, DAC interface circuit design.

A prototype PV inverter has been implemented for the verification of the proposed control scheme using advanced fixed-point DSP controller. The 2kW anti-islanding inverter is designed for an optimal operation of 110V, 60 Hz power distribution system. The PV inverter can operate under a wide dc input voltage range from 40V to 200V. The inverter uses double-conversion when operating in low voltage mode and automatically switches to single-conversion when operating in high voltage mode.



(a) Input voltage and current

(b) Current Harmonic Spectrum

Fig. 9. Experimental results of the inverter with a rated power of 2kW.

The designed PV inverter consists of two major parts: one is a DSP-based inverter controller and the other is an IGBT-based power converter. Fig. 8 shows the photographs of the PV inverter under testing. Fig. 9 shows the experiment results of the implemented grid-connected PV inverter operating at rated output. The inverter achieves an efficiency of 94% at 2kW when operating in single-conversion mode. The output current harmonic spectrum is shown in Fig. 9(b) with a THD of 2.4%.

7. CONCLUSION

The status of technologies development for grid-connected PV inverters has been reviewed. Some practical design considerations are given for a DSP-controlled PV inverter. An integration of the-state-of-art PV inverter control techniques has been developed for a single-chip DSP-controlled grid-connected PV inverter with a rating of 2kW. Experimental results of the designed inverter show a high energy-efficiency of 94% and a low distortion on the line current with a current THD of 2.4% at rated power. It can be concluded that with the integration of advanced power electronics and digital control techniques, low-cost high-efficiency small-power anti-islanding inverters for distributed power generation will be popular home appliances within next ten years.

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研發成果資料表

日期：94 年 1 月 29 日

計畫名稱：太陽光發電技術之研究與新型太陽光變頻器之研製 (2/3)

計畫主持人：鄒應嶼 教 授

計畫編號：計畫編號：NSC 93－2623－7－009－012-ET

論文	**期刊**	
	研討會	1. Kuo-Lung Chai and Ying-Yu Tzou, "Analysis and comparison of single-phase grid-connected PV inverter topologies," Solar World 2005. 2. Yen-Jen Lai, Kuo-Lung Chai, Ying-Yu Tzou, and S. J. Chiang, "Quantitative Design and Implementation of Two-Stage Grid-Connected PV Inverter With DSP-Based Controller," Solar World Conf. Rec., Florida, 2005. 3. William Lin, Daphne Wang, and Ying-Yu Tzou, “Review of PV Inverter Technologies,” Solar World Conf. Rec., Florida, 2005. 4. Kuo-Lung Chai and Ying-Yu Tzou, "Analysis and Comparison of Single-Phase Grid-Connected PV Inverter Topologies," 14th International Photovoltaic Science and Engineering Conference, Chulalongkorn University, Bangkok, Thailand, January 26-30, 2004.
技術報告		1. DSP 控制併網型太陽光變頻器之研製技術報告 2. 低諧波失真數位式電流控制技術報告 3. 微電腦最大功率工作點追蹤控制技術報告
專利	**申請**	模糊推論式最大功率工作點追蹤方法 (申請中)
	獲得	
	應用	
與產業界、研發機構互動成果		產學合作技術移轉系統電子工業股份有限公司
可利用之產業及可開發之產品		綠色能源、發電產業 併網型太陽光變頻器、分散式發電系統、小型風力發電變頻器
技術特點		● 單晶片 DSP 全數位控制技術 ● 低諧波失真同步電流取樣控制技術 ● 模糊推論式最大功率工作點追蹤方法 說明：研製完成一個以單晶片 DSP 控制器為基礎的全數位隔離式雙級單相併網型太陽能光伏變流器，具有電路簡單、效率高、符合市電併聯需求與快速動態響應的特色。採用全數位式設計達到光伏能之高轉換效率、最大功率追蹤及市電併聯技術及保護等多項複雜之快速控制需求，採用多迴路控制方式，回授調整追蹤太陽能板之最大輸出能量，提供穩定之直流鏈電壓；後級則控制兩組半橋式轉換器輸出提供共地點，適合市電併聯需求以發展併聯技術。
推廣及運用的價值		● 可應用於住宅型小型併網發電系統 ● 可結合太陽能與風能應用於綠色能源產業 ● 採單晶片 DSP 控制架構，應用方便，具有商品化潛力 說明：完成一個以單晶片 DSP 為控制核心的 110V、60Hz 併網型光伏變頻器，額定功率為 2kW，最高功率轉換效率達 94%，額定輸出電流總諧波失真為 3.5%，測試性能超越一般商品化之併網型光伏變頻器。

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