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A Review of FPGA-based Implementation related to Electrical Engineering and Contribution to MPPT, Converter and Motor Drive Control

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Abstract: This review is focused on the contribution of FPGA in Electrical Engineering as a system control platform and measurement instruments in three major application i.e. maximum power point tracking (MPPT), converters and motor control system. As system efficiency remain the main focus of photovoltaic (PV) system, interconnected system with various configuration requires rapid processing and more complex control algorithm. As MPPT target the overall system, converters within PV system and hybrid motor control also need a processing platform that is more flexible thus meet the ever-changing demand of the system. Providing much flexible platform that support complex algorithm with more resources is the main attraction of using FPGA platform to develop Electrical Engineering system control application. Implementation of FPGA based system control mainly for optimizing control algorithm for pattern switching, artificial intelligent hybrid system and continuous on-line real time monitoring. In contrast with other digital platform such as microcontroller and application-specific integrated circuit, FPGA remain dominant in computational execution time, higher throughput and flexibility.

Keywords: FPGA; MPPT; DC-DC Converter; Motor Control

1. Introduction

The implementation of Field Programmable Gate Array (FPGA) in Electrical Engineering field mostly common in measurement, controlling algorithm and efficient process development for electrical system or switching devices. The application discussed in this paper covers the contribution of FPGA in maximum power point tracking (MPPT) algorithm, electrical devices switching control and converters application in photovoltaic (PV) system, electrical devices or electrical apparatus. As more advanced technique required for complex configuration of circuits, FPGA offers better approach for more efficient system control development, measurement and real-time monitoring. The implementation of FPGA does not always result in the significant improvement of the system but can be seen as alternative approach for output parameters evaluation.

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MPPT is a technique that charge controllers of the system behave in order to maximize power output. The introduction of FPGA in system control is to accurately tracking the maximum power point (MPPT) of the PV panel, by reducing losses and harmonic distortion, while providing high reliability. Various implementation of MPPT technique which is discuss later in this paper; the integration of FPGA control algorithm must be able to suite its application regardless the weather or radiance condition. Fig.1 illustrated the MPPT Fuzzy control system which generate pulse width modulation (PWM) signal to the converter thus controlling power delivered from PV to the load. Such algorithm is the basis of PV controlling system where MPPT efficiency is measured and become the basis of FPGA based fuzzy controlled implementation [5].

While MPPT covers the overall control system, the second topics discuss the switching algorithm in DC-DC converter (mostly) for system emulation, PV and electric vehicle application, and slight discussion in AC-AC converter. Implementation of FPGA clearly focused on designing the most suitable switching algorithm or switching pattern for cascaded/complex system in order to achieve low harmonics distortion either as regulated output or feedback to the system. The approach of each system is design according to the specific requirement which applied in different control system. Fig. 2 illustrated the FPGA implementation in switch driver control used for buck converter; with additional monitoring capability and inductor over-current protection [12]. Such implementation of FPGA in synchronous buck converter helps increases the overall system capability without incurring additional control chips thus improve the system flexibility per chip.

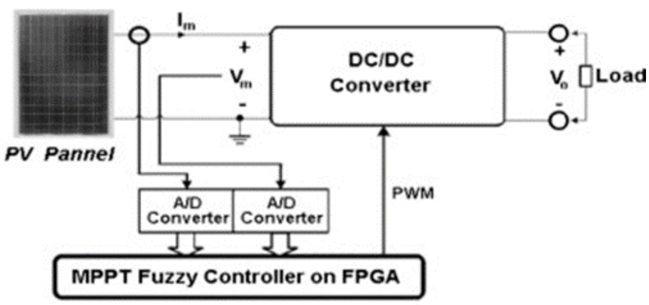

Figure 1: MPPT Control System integration with Fuzzy Logic Connected to PV Modules [5]

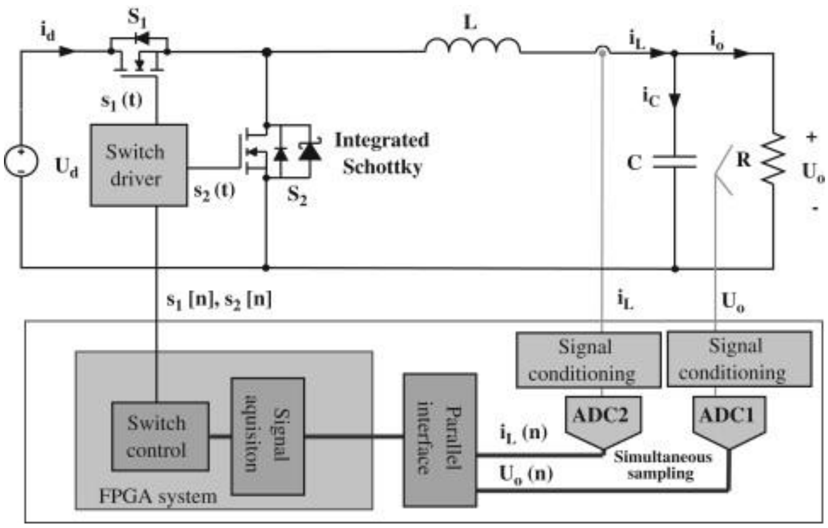

Figure 2: FPGA-based Synchronous Buck Converter [12]

Industrial motor control is dominated by microcontroller unit or ASIC; the final review in this paper is focused on implementing motor control using FPGA and how it can be manipulated in order to improve efficiency and productivity. Being the most utilized electrical machine, DC motor are heavily used in industrial application or as home appliance whether as independent load or with complex configuration. Most common technique of controlling dc motor speed is by means of PWM, but with the flexibility of FPGA that support complex circuitry, more complex algorithm can be implemented for specific configuration of dc motor. Induction motor on the other hand plays major roles in industrial process, where MCUs control is the most commonly use technique either for motor start-up, switching algorithm or enhancement of process efficiency. Integration of FPGA is indeed crucial for complex switching algorithm but cost ineffective for most cases which implies the use of conventional MCUs controller. Fig. 3 depicted the possibility of controlling and real-time on-line measurement using FPGA platform that can be used in fault detection [15]. The possibility of various combinational and hybrid technique is further discuss in the next topic.

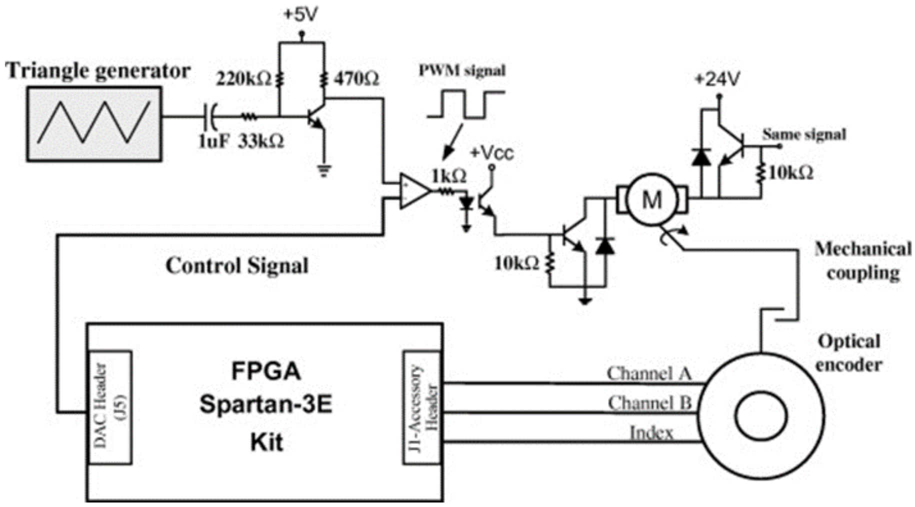

Figure 3: FPGA-based DC Motor Speed Control Block Diagram [15]

Implementation of FPGA also have been seen in continuous real-time on-line power monitoring with the assistance of neural network in detection of additional non-linear load which affected the general machine-tool condition [22]. A comparative study of conventional strategies with fully digital implementation of FPGA, also being carried out to verify the fundamental concept. Fundamental concept evaluation such as FPGA based single-phase PWM boost rectifier via the sliding mode proven that FPGA implementation improve the overall system control function such as distortion and harmonic grid current reduction, adaptability of working at unit power factor and capability of controlling dc link voltage even in fluctuation condition [25]. However these studies contribute in more focus areas and giving less impact to power electronic control algorithm in contrast with implementation for MPPT, converter and motor control which inter related with each another. Further review of related studies on MPPT, DC-DC switching algorithm and motor control in the next sections helps understand the significant of implementing FPGA in Electrical Engineering thus diversify the control algorithm technique in the related area.

2. Maximum Power Point Tracking (MPPT) algorithm

The improvement of total harmonic distortion (THD), power factor (PF) and tracking range of MPPT can be achieved by precise and efficient switching algorithm which applied with MPPT. Mixed staircase-PWM technique perform by means of sorting algorithms reduces the device number in switching mode for cascaded H-bridge photovoltaic (PV) [1]. The use of FPGA approach, helps coordinate MPPT voltage references and dc-link voltage by the use of sorting algorithm to increase overall system efficiency even in mismatch condition. FPGA implementation also resulted in faster per cell MPP tracking assuring more stable operation even with uneven irradiation condition. The system proposed shown the capability of establishing 2.5% THD while keeping power factor (PF) at almost unitary for a five-level grid-tied PV cascaded H-bridge (CHB) inverter [1].

The use of perturbation and observation (P&O) could generate the MPP algorithm but generating gate signal to inverter require more precise and controlled algorithm. Synthesizing the adjustment of modular index and phase angle onto FPGA to generate space vector pulse width modulation (SVPWM) will resulted in high dynamic performance with low THD [2]. The implementation of such technique reduces less voltage stress imposed on the switching devices and increase the system capability to operate at a lower switching frequency. It will provide various switching states setting, optimization of switch pattern thus improving dc link voltage utilization.

Global maximum power point (GMPP) method operating under partially shaded condition is an enhancement of MPP algorithm which focus for uneven irradiance condition [3]. Under load capacitor charging mode, the current sensor and voltage values that gives P-V curves is feed to FPGA based algorithm that adjust the duty cycle of the boost dc-dc converter. In contrast with sorting algorithm, MPP algorithm require no multiple MPPT device, thus allowing combination of different type and power rating PV panels [2],[3].

Carrier Phase Shifting Sinusoidal Pulse Wave Modulation (CPS-SPWM) was introduced specially for converter and multi-level converter switching strategies [4]. This modulation strategy is adaptive to high power occasion, maximize improvement of waveform, decrease output harmonics and capacity of filters. The use of FPGA offers flexibility of designed algorithm without altering the hardware. The capability of concurrent operation possess by FPGA with less hardware, circuit flexibility and support of circuit complexity make it as most favourable choice.

A fuzzy logic MPPT controller offers additional parameters of climate variable by including PV cell temperature [5]. The controller system is based on fuzzy heuristic rules, consists of stepwise adaptive search, leads to fast convergence and perform well with respect to change in climate condition. Fuzzy controllers MPPT controller however does not improve the overall response but comparatively with higher glitches compared with conventional P&O method. Though further improvement is expected for adaptive fuzzy logic MPPT controller in the near future.

Comparative study of intelligent method (IMs) in MPPT investigate neural networks (NN), fuzzy logic (FL), genetic algorithm (GA) and hybrid system conclude that fuzzy logic generic algorithm (FL-GA) controller outperform the other IMs in terms of accuracy, rapidity, flexibility, power consumption and simplicity of implementation [7]. The advantages of embedding FPGA in MPPT controller is obvious, faster converging speed, good performance, improve efficiency, low power consumption, no divergence during varying weather condition. Further study of FPGA based IMs conclude that the implementation of such IMs for the case of partially shading condition should be revised by modifying or combining IMs with other classical technique [7].

FPGA-based real time simulation for PV system outline two main block control circuit; MPPT and inverter control [6]. Incremental Conductance (IncCond) algorithm is used to impose the optimal operating point of PV generator whereas de-coupled active-reactive power control algorithm (PI type controller, SPWM generator and synchronous PLL devices) is used to control the single phase inverter. The simulation result demonstrate that FPGA can provide the entire control of grid-connected PV, simplify the control circuit computation requirement and easier to implement.

The implementation of FPGA in power electronics switching system especially for MPPT algorithm uses in PV array offers various control technique. Most commonly use method is by controlling the duty cycle of switching devices, thus manipulating the overall efficiency, computation time, complexity of device configuration which resulted in improvement of MPPT regardless the radiance condition. The introduction of fuzzy logic controller, however, does not improve the MPPT response, which require further development of controller algorithm [5]. Although FPGA offer faster response for most cases, further study of IMs implementation methods proves that under uneven irradiance condition, combination with classical method is essential to improve the efficiency of MPPT algorithm [7]. A more flexible FPGA-based circuit controller design can be implemented for multi-tiers PV system with multi-level inverters and converters which will contribute to effective and reliable MPPT.

3. DC-DC and AC-AC Converters

As technologies of green power generation evolves, algorithms for controlling converters become more significant. The difficulty of implementing analog/mixed signal (AMS) circuit in FPGA, leads to the development of AMS emulation that exploits fixed-point modelling and digital signal processing (DSP) implementation technique [9]. The model is tested using buck type switching converter test platform. The emulation of such model, will provide a solution of a start plan at the early stage of design and test flow. The evaluation of test model shows that more complex analog circuit can be implemented. Modelling a complex AMS circuit on FPGA, requires cascaded signal processing block; however this model applies with fixed word length and manually sampling frequency check. While FPGA resources is at a disposal, the multicriterion optimization of word length need to be work on.

The implementation of FPGA on DC-DC boost switching converter, is to overcome voltage overshooting in the voltage output [10]. A test on interchangeable load impedance point out that the propose control algorithm reduces voltage spikes and remove static voltage error. Further analysis conclude that the controller with higher order than PID, can be implemented on FPGA without any impact on control algorithm execution time.

The use of interleaved DC-DC boost converter topology in Proton Exchange Membrane Fuel Cell (PEMFC) will minimize the current ripple thus optimizing its lifetime [11]. The detection of power switch failure such as Open Circuit Faults (OCFs), does not force the DC-DC converter to seize its operations. To ensure a continuity of service and/or reduce the undesirable effects of degraded operating modes, a fault-tolerant DC/DC converter topology or/and a Fault-Tolerant Control (FTC) must be used. The contribution of FPGA for FTC is by providing the control algorithm for at PWM gate signals according to the faulty leg thus keeping current ripple low which resulted in the improvement of fuel cell performance [11].

The implementation of Lyapunov function in order to stabilize the switching sequence of DC-DC buck converter requires multiple coordination which include features of protection, steering, monitoring and communication. A hybrid algorithm which applies direct method of Lyapunov (DML) and control Lyapunov function (CLF) ensure better result of obtaining stability and good voltage output regulation [12]. Additional features such as inductor over-current protection are included in the switching control as parallel operation of the FPGA allows for execution of the main processes and additional logic functions to run simultaneously.

AC-AC variable frequency power conversion system uses AC-AC matrix converter which can operate in low frequency cycloconverter and high frequency cycloinverter [13]. The ability to directly affect the frequency conversion of power is made possible using trapezoidal modulation technique. This technique is simpler with faster real-time waveform generation and higher fundamental output voltage compared to other modulation technique. FPGA-based trigger control circuit will generate trapezoidal modulated trigger signal which fed to the driver of frequency converter to get the acquired output voltage waveform. The output voltage produce minimal undesirable harmonics components but with unequal THD in cycloconverter and cycloinverter mode.

A novel real-time digital feedback control of single phase to three phases Converter (SPTTPC) for electrical drives implemented using FPGA will eventually generated gate pulses to single unit rectifier unit using SVPWM technique which finally connected the inverter output to electrical drives [25]. As mentioned earlier, SVPWM strategies are capable to produce high fundamental output current with low harmonic distortion. FPGA for SPTTPC control seems to reduce the high switching loss, high stress, electromagnetic interference and total harmonic distortion of power switching devices.

AMS circuit emulation is merely a model which represent the closest criteria of DC-DC buck switching algorithm in contrast with SPICE simulation [9]. Although is it helpful to the designer at the early stage of the design it hasn't been proven to work in real-time. The flexibility of FPGA platform which offers simulation of a designed model and real-time implementation helps the designer at design stage or verification at field test. With the help of FPGA, control algorithm for DC-DC converter such as interleaved topology or Lyapunov function, proof that the use of FPGA is not restricted to switching algorithm, but also can be implemented in detecting fault, as measurement apparatus and protection for a design system [12]. Regardless of the algorithm function, FPGA can generate cleaner switching patterns that will improve regulated voltage output which later contribute to more efficient system. Research in the use of FGPA in assisting AC-AC converter control algorithm still emphasise on the switching algorithm as measurement, but protection features in AC-AC converters requires different approach [13]

4. Motor Control

The use of low-cost FPGA in multi-unit motor control algorithm is in relatives with the increment of cost incur for the total system. Although parallel processing is essential in significantly reduced execution time, the resources utilization should be optimized. Using a system-level time-division multiplexing, large identical complex control algorithms can be simplified into a single compact algorithm; which is then fitted into low-cost FPGA [14]. Controlling permanent magnet synchronous motor (PMSM) with SVPWM often exceed the resource availability, but with system-level time-division multiplexing approach, this issue can be resolved. A multi-motor control system using commercial MCUs will have limitation in computational bandwidth and dedicated PWM peripherals. Thus, a control system containing more than four motor units is more costly for low-cost FPGA in comparison with multi-unit MCUs solution but deliver better computational performance with system integration on a single chip.

Adaptive fuzzy logic controller (ALFC) require a high complex control algorithm. The implementation of fuzzy logic controller with Proportional Integral Derivative Adjusting Mechanism (ALFC-PIDAM) is made possible by FPGA integration, as is reduces the computational complexity of different sets of an adaptive fuzzy algorithm [15]. The proposed controllers are implemented in FPGA for real time control of speed in the non-linear DC motor, which evaluate the dynamic performance of DC motor drive while the AFLC and the AFLC-PIDAM are applied in a speed control loop. Input from feedback loop control is treated as membership function which later use as decision element in fuzzy rules in determining speed control.

FPGA-based motor speed controller integration with FLC and proportional-integral (PI) aimed to improve tracking performance and eliminate load disturbance in non-linear DC motor [16]. As conventional PI controller remain superior in industrial control system, implementation of FLC-PI could bring more benefit to industrial process. The capability of integration large number of fuzzy logic in a single circuit, reconfigurable and adaptive to various computational task makes FPGA as dominant choice compared to other platform. Conventional PI controller resulted in lack of smooth transition between desired speed, presence of overshoot and higher rise time. FPGA integration of FLC-PI is observed to have less oscillation, zero overshoot and less rise time.

While the previous two approach implies to dc motor, fuzzy logic integration with PWM generated is used to vary the speed in induction motor [15],[16]. As the importance of variable frequency drive is required for varying induction motor speed, implementation of fuzzy logic in real time application becomes essential. The PI approximated fuzzy control integrations in FPGA, however does not produce significant improvement in regulated output but rather acceptable result. FPGA implementation of integrating PWM and fuzzy control in induction motor indicates that a comparative study of other hybrid fuzzy control should be carried out for the benefit of industrial process [18].

Vibration analysis has been one of the significant approaches for induction motor failure detection especially in industrial equipment. Faster diagnosis of fault will guarantee the overall process efficiency. Fitting online vibration measurement for continuous measurement and reliability diagnosis to machine under test (MUT) would improve fault detection of induction motor [17]. The system consists of axis piezoelectric accelerometer, data acquisition system and FPGA as signal processing unit. Specific pre-filtering modules would assist in better diagnosis especially with FFT based vibration analysis. Three filters modules which integrated in FPGA offers reconfigurable open architecture and observed to have low complexity with minimal latency.

FPGA implementation is not restricted to complex algorithm control but also as fundamental control such as motor driver and voltage/frequency control. Comparative study of three-phase induction motor drive between soft drive approach and integration of FPGA-based SPWM, increase the flexibility of motor driver, low cost and high performance [20]. The control algorithm is achieved by adjusting modulation index and frequency thus provide controlling switching pulses for the inverter block. Another comparative study of voltage/frequency control and classical squirrel-cage of induction motor shows that smooth control of speed is possible with FPGA and result are closer to set speed [21]. The integration of FPGA-based induction motor control is an alternative choice for the industrialist over conventional MCUs control for control system that require high processing and input/output handling speeds.

A simplified start-up method for AC synchronous machine is achievable by feeding stator voltage with a ramp frequency [19]. Implementation of such algorithm with SVPWM is carried out for the ventilation of a greenhouse by means of FPGA. A comparative study with MCUs shows both implementation yield to a great performance for the fan drive in terms of smooth transient current but FPGA remain superior in terms of optimal utilization resources and algorithm execution speed. The AC synchronous machine start up is design using frequency profile acquired from desired rotor velocity which require a closed-loop control system. Although it requires a simple algorithm, integrating with complex SVPWM to obtain rotor velocity prove to be a challenge for conventional MCUs control.

Motor control is often applied using MCUs which is cost effective but rather complicated when involving a big scale or complex system. Regardless of control algorithm used FPGA offers faster execution time but control algorithm must be optimized to balance the cost increment incurs. Integrating FPGA with fuzzy logic algorithm could provide a simpler compact algorithm but require coordination of membership function and fuzzy rules to produce efficient speed controller system. Integrating an independent FLC into FPGA does not produce optimal speed control, and should be complemented by PIDAM, PI controller or PWM [15], [16], [18]. The best combination is rather described by the application of the designed process. The advantages of FLC based on FPGA is flexible design (the membership function and rule base can be easily change), featured accuracy, high reliability, cost improvement and high speed. A more straight forward application such as induction motor drives or fault detection contribute the equal significant to industrial control process. As more industrial process emphasize on rapid processing with parallel multiple input/output, FPGA is a requirement to optimize the control process which require minimum external components.

5. Conclusion

The contribution of FPGA in Electrical Engineering is significant in providing a better platform for control system. Integrating FPGA helps provide better solution for complex algorithm thus improving overall system efficiency which proven by samples discussed related to MPPT, converter application or motor drives. FPGA is a custom built solution which may implies specific control strategies of industrial control or applications. As FPGA implementations not restricted of algorithm generation, fundamental application such as measurement (fault detection), closed loop control (feedback) and continuous on-line monitoring, plays equal role in establishing FPGA as dominant platform in developing system control in comparison with other platform such as MCUs and ASICs.

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