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FPGA-Based Three Phase Inverter Control System for VSCF Wind Turbine

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***Abstract*—Following to the important increase of electrical power demand around the world, many researchers are attempting to find new energy sources away from the fossil fuels. In this regard, the utilization of renewable energy resources, such as solar, geothermal, and wind energy, appears to be one of the most efficient and effective ways in achieving this target. Recently, wind power as a potential energy has grown at an impressive rate in the most emerging countries of the world. At the same time as that happens the power electronics knows enormous progress, increasing adoption of FPGAs in digital switched-mode power supply (SMPS) control is driving significant interest in improved platforms for development. In this paper, we propose a new methodology for high level system design of SMPS controllers and developed for variable speed constant frequency (VSCF) wind power generator. The feasibility, validity and accuracy of the approach are evaluated through the design and testing of a three-phase DC-to-AC inverter.**

Key-Words—*Wind Turbine, FPGA Control, Inverter, Power System, LabVIEW, Multisim, Virtual Instrument*.

I. INTRODUCTION

THE demand for energy is increasing at an exponential rate due to the exponential growth of world population. The combined effect of the widespread depletion of fossil fuels and the gradually emerging consciousness about environmental degradation has given priority to the use of conventional and renewable alternative energy sources such as solar, wind and solar-hydrogen energies [1]. The rapid development in wind energy technology has made it an alternative to conventional energy systems in recent years. Parallel to this development, wind energy systems have made a significant contribution to daily life in developing countries, where one-third of the world's people live without electricity [2, 3].

Wind energy, as one of our most abundant resources, is the fastest growing renewable energy technology worldwide as shown in Fig. 1. Improved turbine and power converter designs have promoted a significant drop in wind energy generation cost making it the least-expensive source of electricity—from 37 cents/kWh in 1980 down to 4 cents/kWh in 2008. In 2008, wind energy systems worldwide generated 331,600 million kWh, which is 1.6% of total electricity generation—making wind the second highest resource after hydroelectric power (16.6%), while the photovoltaic (PV) technology contribution was only 0.1%. The United States alone possesses more than 8,000 GW of land-based wind resources suitable for harnessing, and an extra 2,000 GW of shallow offshore resources. With U.S. total electricity generating capacity at 1,109 GW in 2008, the untapped wind sources in United States is almost 8 times as large. Global wind movement is predicated on the earth's rotation, and regional and seasonal variations of sun irradiance and heating. Local effects on wind include the differential heating of the land and the sea, and topography such as mountains valleys. We always describe wind by its speed and direction. The speed of the wind is determined by an anemometer, which measures the angular speed of rotation and translates it into its corresponding linear wind speed in meters per second or miles per hour. The average wind speed determines the wind energy potential at a particular site. Wind speed measurements are recorded for a 1-year period and then compared to a nearby site with available long-term data to forecast wind speed and the location's potential to supply wind energy.

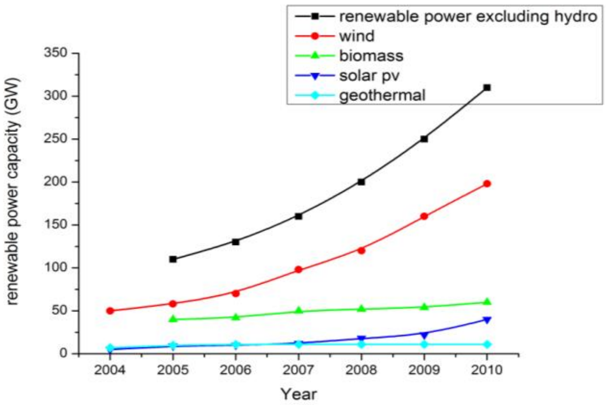


Figure 1. Worldwide electricity generationsfor wind, biomass,geothermal, and solar resources, years (2006-2011), data source REN21renewable global status report

The power converter is the interface between the load/generator and the grid. The power may flow in both directions, of course, dependent on topology and applications. Three important issues are of concern using such a system. The first one is reliability; the second is efficiency and the third one is cost. For the moment the cost of power semiconductor devices is decreasing 2-5 % every year for the same output performance and the price pr. kW for a power electronic system is also decreasing.

A high competitive power electronic system is adjustable speed drives (ASD) and the trend of weight, size, number of components and functions in a standard Danfoss Drives A/S frequency converter. It also shows that more integration is an important key to be competitive as well as more functions become available in such a product.

The increasing adoption of FPGAs controllers for high-frequency digital SMPS [4]-[7] is raising considerable interest in finding the most efficient and appropriate development processes for power electronics control systems, given that the FPGA embedded systems development represents a significant paradigm shift compared to that for microprocessors, micro-controllers and DSPs. A typical digitally-controlled SMPS and suitable controller targets based on unit cost for different power levels are shown in Fig. 2 (a) and (b), respectively. FPGAs provide an attractive architecture for power electronics control systems, due to their ability to produce custom high-frequency, low-latency (sub 1-ns) gating signals, ability to place digital pulse-width modulators (PWM) and dead-time circuits in dedicated hardware, high speed digital signal processing capabilities, and silicon-gate-level (SGL) user configurability. Due to the fast changing requirements of the smart grid and renewable energy markets, the inherent field re-configurability of FPGAs is also attractive from the perspective of long-term support, maintenance and interoperability with evolving standards and communication protocols.

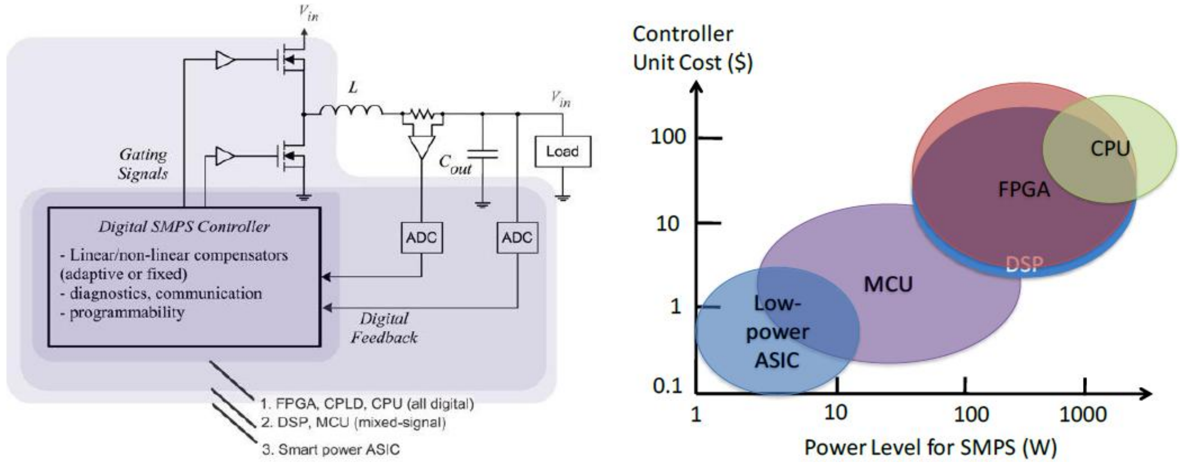


Figure 2. (a) SMPS and (b) spectrum of suitable control targets for mass production

II. WIND TURBINES

Among the emerging 'sustainable' sources of electric power, wind is both the largest and fastest growing. Fig. 3 shows a view of a wind farm, with a number of 1.5 MW wind turbines. These units have a nearly horizontal axis with a blade disk diameter of about 77 m and 'hub height' of 65 to 100 m, depending on site details [8].

Power generated by a wind turbine is, approximately:

$$P = \frac{1}{2} \times C_p \times \rho_{air} \times A \times u^3. \qquad (1)$$

where ρ is air density (about 1.2 kg/m^3); u is air velocity, so that (½) $\rho\ u^2$ is kinetic energy density of wind entering the disk of area A; C_p is the "power coefficient ", a characteristic of wind speed, rotor angular velocity and blade pitch angle. It has a theoretical maximum value of about 59% but as a practical matter usually does not exceed about 50%. Because this coefficient is a function of wind and rotor tip speed (actually of the advance angle), wind turbines work best if the rotational speed of the rotor is allowed to vary with wind speed. More will be said about this in the discussion the kinds of machines used for generators, but the VSCF machines used for wind generators are among the most sophisticated of electric power generators. They start generating with wind speeds of about 3 m/s, generate power with a roughly cubic characteristic with respect to wind speed until they reach maximum generating capacity at 11–13 m/s, depending on details of the wind turbine itself, and then, using pitch control, maintain constant rotational speed and generated power constant until the wind becomes too strong, at which point the turbine must be shut down. This 'cut-out' speed may be on the order of 30 m/s.

Figure 3. Cedar Creek 2 Wind Farm, colorado ,USA.

III. VARIABLE SPEED CONSTANT FREQUENCY (VSCF) WIND POWER GENERATOR

Recently, with the rapid development of wind power, the variable-speed constant-frequency wind turbine has become the main type in the global market. Although the performance of variable-speed constant-frequency wind turbine is much better than fixed-speed wind turbine, it is still an impact to the grid while it is integrated into the power system for variation of wind speed; therefore it is necessary to study the new type of wind turbines integration characteristics.

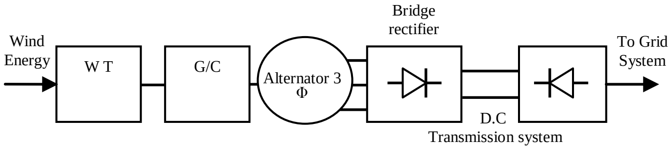


Figure 4. Variable speed constant frequency scheme

This scheme, involving small wind generators is commonly used in autonomous applications such as street lighting. Due to variable speed operation, it yields higher power for both low and high wind speeds. Both horizontal axis and vertical axis turbines are suitable.

Greater efficiency in wind turbine systems [9] is achieved by allowing the rotor to change its rate of rotation as the wind speed changes. For this reason, the wind turbine system is decoupled from the utility grid and a variable speed operation is implemented. But electrical output frequency should be constant!

Permanent Magnet (PM) machines have major advantages for wind turbine applications: Efficiency and power density are both high, but they are inherently synchronous (i.e., constant speed/frequency).

IV. FPGA

Field Programmable Gate Array or FPGA [10]-[15], as it is more widely called, is a type of programmable device. Programmable devices are a class of general-purpose chips that can be configured for a wide variety of applications. The first programmable device, which achieved a widespread use, was the PROM (programmable Read-Only Memory). PROMs, a onetime programmable device comes in two basic versions: (1) The Mask-Programmable Chip programmed only by the manufacturer and (2) The Field programmable Chip programmed by end-user.

Field-programmable gate arrays (FPGAs) [16]-[18] are reprogrammable silicon chips. Ross Freeman, the cofounder of Xilinx, invented the first FPGA in 1985. FPGA chip adoption across all industries is driven by the fact that FPGAs combine the best parts of application-specific integrated circuits (ASICs) and processor-based systems. FPGAs provide hardware-timed speed and reliability, but they do not require high volumes to justify the large upfront expense of custom ASIC design.

Reprogrammable silicon also has the same flexibility of software running on a processor-based system [19], but it is not limited by the number of processing cores available. Unlike processors, FPGAs are truly parallel in nature, so different processing operations do not have to compete for the same resources. Each independent processing task is assigned to a dedicated section of the chip, and can function autonomously without any influence from other logic blocks. As a result, the performance of one part of the application is not affected when you add more processing like Fig. 5.

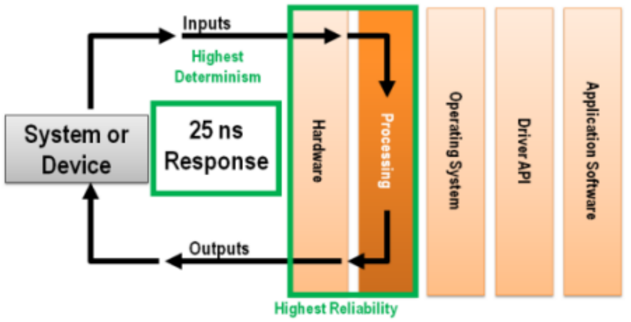


Figure 5. One of the benefits of FPGAs over processor-based systems is that the application logic is implemented in hardware circuits rather than executing on top of an OS, drivers, and application software (*National Instruments*).

Every FPGA chip is made up of a finite number of predefined resources with programmable interconnects to implement a reconfigurable digital circuit and I/O blocks to allow the circuit to access the outside world.

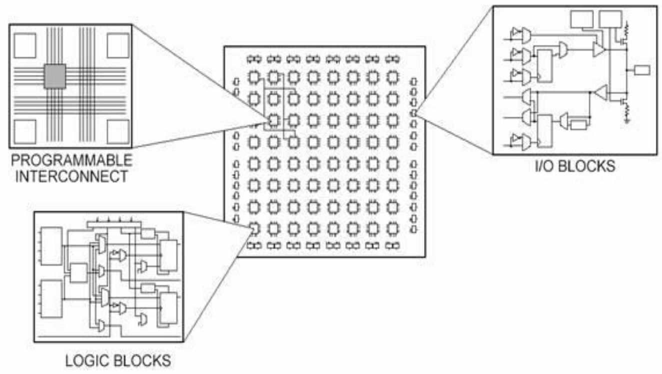


Figure 6. The Different parts of an FPGA (*National Instruments).*

FPGA resource specifications often include the number of configurable logic blocks, number of fixed function logic blocks such as multipliers, and size of memory resources like embedded block RAM. Of the many FPGA chip parts, these are typically the most important when selecting and comparing FPGAs for a particular application.

The configurable logic blocks (CLBs) are the basic logic unit of an FPGA. Sometimes referred to as slices or logic cells, CLBs are made up of two basic components: flip-flops and lookup tables (LUTs). Various FPGA families differ in the way flip-flops and LUTs are packaged together, so it is important to understand flip-flops and LUTs.

V. VHDL GRAPHICAL LANGUAGE

The emergence of graphical HLS design tools, such as LabVIEW, has removed some of the major obstacles of the traditional HDL [20]-[21] design process. The LabVIEW programming environment is distinctly suited for FPGA programming because it clearly represents parallelism and data flow, so users who are both experienced and inexperienced in traditional FPGA design processes can leverage FPGA technology. In addition, so that previous intellectual property (IP) is not lost, you can use LabVIEW to integrate existing VHDL into your LabVIEW FPGA designs.

Then to simulate and verify the behavior of your FPGA logic, LabVIEW offers features directly in the development environment. Without knowledge of the low-level HDL language, you can create test benches to exercise the logic of your design. In addition, the flexibility of the LabVIEW environment helps more advanced users model the timing and logic of their designs by exporting to cycle-accurate simulators such as Xilinx ISim.

LabVIEW FPGA compilation tools automate the compilation process, so you can start the process with a click of a button and receive reports and errors, if any, as compilation stages are completed. If timing errors do occur because of your FPGA design, LabVIEW highlights these critical paths graphically to expedite the debugging process.

VI. THREE-PHASE SINE-Δ PWM INVERTER

Fig. 7 shows circuit model [22] of three-phase PWM inverter and Fig. 8 shows waveforms of carrier wave signal (V_{tri}) and control signal ($V_{control}$), inverter output line to neutral voltage (V_{A0},V_{B0}, V_{C0}), inverter output line to line voltages (V_{AB}, V_{BC}, V_{CA}), respectively.

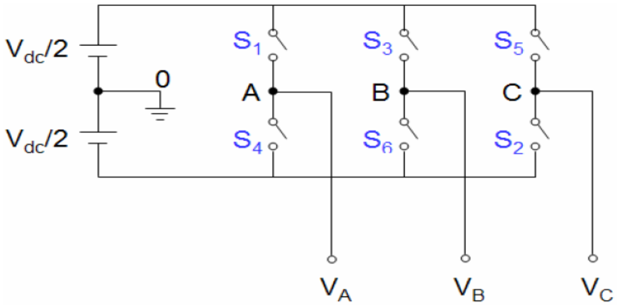


Figure 7. Three-phase PWM inverter.

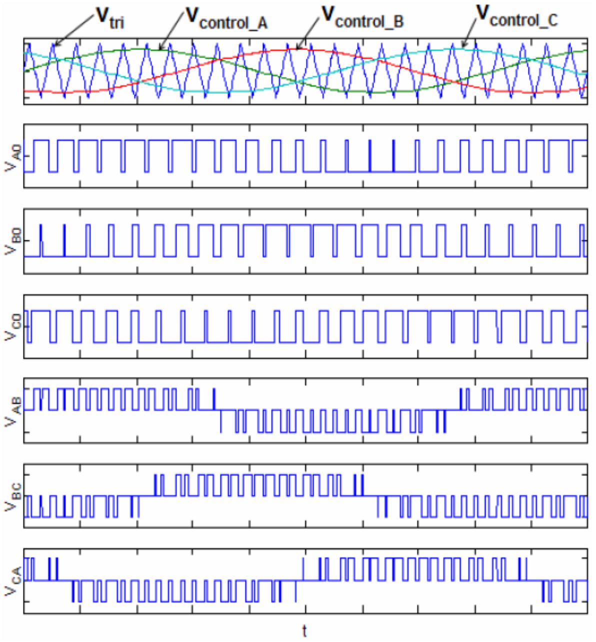


Figure 8. Waveforms of three-phase sine-Δ PWM inverter.

As described in Fig .8, the frequency of V_{tri} and $V_{control}$ is f_s and f_1 where, f_s is the PWM frequency and f_1 the fundamental frequency, respectively. The inverter output voltages are determined as follows:

$$\text{if } V_{control} > V_{tri},\ V_{A0} = V_{dc}/2 \quad (2)$$

$$\text{if } V_{control} < V_{tri},\ V_{A0} = V_{dc}/2 \quad (3)$$

where, $V_{AB} = V_{A0} - V_{B0}$, $V_{BC} = V_{B0} - V_{C0}$, $V_{CA} = V_{C0} - V_{A0}$

VII. SOFTWARE DEVELOPMENT

The feasibility, validity and accuracy of the new design methodology [23] containing the desirable characteristics described in Section VI is evaluated through the design and testing of a three-phase DC-to-AC inverter. An experimental inverter was assembled using a low-power off-the-shelf three-phase IGBT intelligent power module (IPM), and the high-level FPGA control software was validated using co-simulation techniques [24].

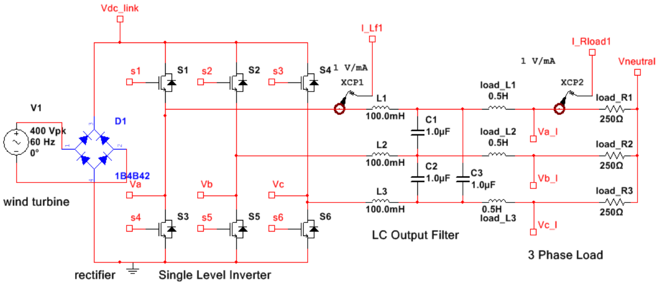
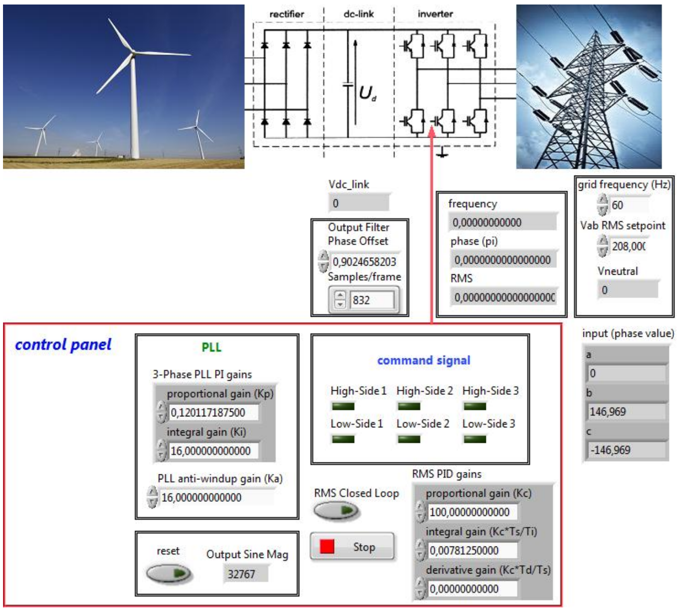


Figure 9. Wind turbine, rectifier, three-phase inverter co-simulation schematic in multisim



Vdc_link: 0
Output Filter Phase Offset: 0,9024658203
Samples/frame: 832
frequency: 0,00000000000
phase (pi): 0,0000000000000000
RMS: 0,0000000000000000
grid frequency (Hz): 60
Vab RMS setpoint: 208,00(
Vneutral: 0
3-Phase PLL PI gains
proportional gain (Kp): 0,120117187500
integral gain (Ki): 16,000000000000
PLL anti-windup gain (Ka): 16,000000000000
Output Sine Mag: 32767
RMS PID gains
proportional gain (Kc): 100,00000000000
integral gain (Kc*Ts/Ti): 0,00781250000
derivative gain (Kc*Td/Ts): 0,00000000000
input (phase value)
a: 0
b: 146,969
c: -146,969

Figure 10. The LabVIEW graphical user interface of the FPGA control of the inverter

The system simulation graphical interface in Fig. 10 includes user-defined parameters for the PID control, variable RMS output set-point, output filter phase offset, and PLL gains. Real-time visualization of the output line voltage compared to the grid voltages is displayed. This system is co-simulated with Multisim design in Fig. 9.

The PLL works as follows:

- Line voltages are measured sent through a Park transformation giving the mains voltage as DC-components.
- A phase detector uses the low pass filtered values of the mains voltage DC-components to determine the angle deviation between real mains voltage and angle reference.
- A derivator followed by a low pass filter stage determines the frequency deviation between reference and mains voltage.
- Phase and frequency difference are summed in a weighing mechanism to an error signal. It is fed to the PI controller that governs the frequency input signal to the reference angle generator, the VCO.
- When the phase locked loop is unlocked, and the frequency deviation is beyond a threshold value, the weighing mechanism attenuates the angle deviation signal gradually so the error signal is dominated by the phase deviation. The VCO frequency is now directed towards the mains frequency, until it becomes close enough for the PLL to lock on to the mains voltage gracefully.

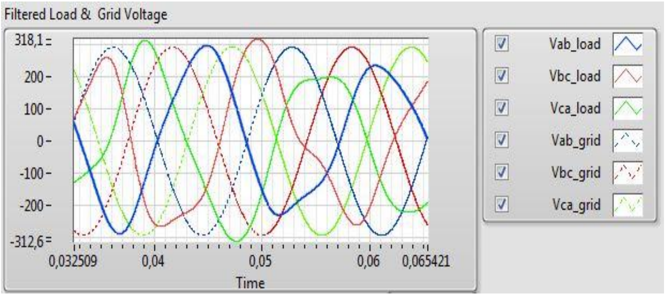


Figure 11. System simulation after 0.03 sec

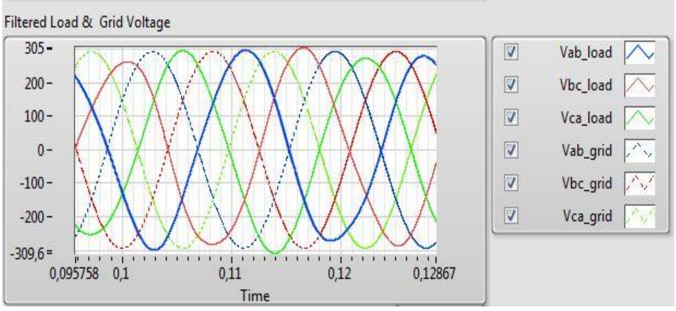


Figure 12. System simulation after 0.1 sec

The simulation results with output filter phase offset equal to 90.24°showed in Fig. 11 that after 0.03 sec of running the system, the output voltage of the 3-phase inverter is not aligned to the grid voltages since the feedback system is still at its initial stage. The simulation in Fig. 12 shows that it takes about 0.1 sec for the inverter output to align to the grid line voltages.

This unparalleled approach of system simulation that includes all of the dynamics between the analog circuitry and the FPGA control logic enables early evaluation of the system performance as well as saves simulation time and prototyping cost.

VIII. CONCLUSION

The local population should be able to absorb the development of a country or region. The people should be financially, mentally and physically able to support the improvement in the quality of their lives. We want the entire population to have access to uninterrupted supply of electricity. This puts a huge burden on the limited fossil fuel resources. The benefits of using wind power over other resources lies in its minimum operational cost.

Variable speed wind turbines feature higher energy yields and lower power fluctuations than fixed speed wind turbines. The last feature is particularly important as flicker may become a limitation to wind generation on power systems. Also, variable speed wind turbines produce more reduced loads in the mechanical parts than fixed speed wind turbines, but this analysis has not been carried out in this paper.

As we will detail in the full paper, we have successfully demonstrated a new system-level design platform and methodology for FPGA-based digitally controlled SMPS design that satisfies the requirements to control the three phase inverter for VSCF wind turbine.

This new methodology allows designers to seamlessly leverage the computational advantages of next generation FPGAs for digitally controlled power electronic converters without requiring any knowledge of HDL languages.

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