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PSCAD응용:태양광및연료전지발전시스템의계통연계를 위한 단상인버터모델

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APSCADApplication:Single-phaseUtility-ConnectableInverterModelforPVorFCSystem

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Abstract - The purpose of this paper is to describe and demonstrate how a utility-connectable inverter for photovoltaic or fuel-cell applications can be well modeled using PSCAD/EMTDC. In this paper, a single-phase IGBT inverter using SPWM is modeled. Simple voltage magnitude and phase controls are implemented using PSCAD's PI controller, PLL, and a "user defined" component called Modulo (found in their extensive collection of example circuits). The circuit model also takes advantage of PSCAD's interpolated firing pulse option, which provides improved simulation results by preventing errors from being introduced when switches fire between time simulation steps. Additionally, PSCAD's Online Frequency Scanner for FFT is utilized for a demonstration of PSCAD's frequency-domain analysis capabilities.

1. Introduction

The purpose of this paper is to describe and demonstrate how a utility-connectable power electronic DC-AC inverter can be well modeled using Manitoba HVDC Research Centre's industry-standard PSCAD/EMTDC software for power system design and simulation. This type of inverter is commonly used in distributed power generation systems, and the model presented in this paper is intended for application in photovoltaic or fuel-cell systems. The great advantage of PSCAD over other simulation software is its combination of widespread acceptance for traditional power system modeling and its capability for accurate modeling of power electronic sub-systems. This combination facilitates useful studies of distributed generation (DG) systems and their impact on connected systems and the utility grid. Obviously, separate analyses of the DG and connected systems would not be acceptable since it is their interaction that is of interest [8]. In this paper, the focus is on modeling of the power electronic inverter since it is the foundation of a good study on DG.

2. Body

2.1 DescriptionofInverter

Figure 1 shows a single-phase DC-AC inverter as modeled in PSCAD. Using the IGBT component with snubber option disabled, back diodes were added and the full-bridge converter was quickly constructed using the "Wire-mode" feature. The DC source used is admittedly an oversimplification of the combination of DC-DC converter and a photovoltaic array or fuel-cell stack; however, models of those components will have to wait for a future effort to enhance the realistic nature of such a model.

The inverter is connected through a 5 kW isolation transformer to one phase of the utility grid that is in parallel with a purely resistive load. The values chosen for the Thevenin equivalent of the grid were arbitrarily chosen for sake of simplicity. As suggested in the introduction, PSCAD should be used to construct a reasonable model of any connected systems for a detailed analysis of a DG system (which is not the purpose of this paper).

The LC filter was designed based on an algorithm for single phase PWM inverters [1]. This filter design methodology takes into account the following factors: DC input voltage, AC output voltage, output current, output frequency, switching frequency, average desired output harmonic voltage magnitude.

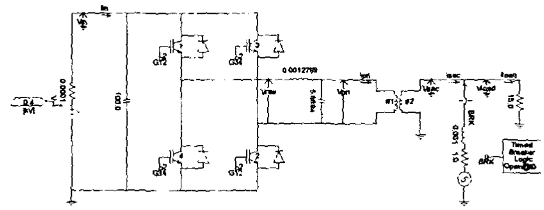

Figure1 - Inverter Circuit Schematic

In order to facilitate testing the inverter in both stand-alone and grid connected modes, a timed breaker component was added to switch-in the utility grid after a given time in the simulation. In this simulation, the switch was initially open at time zero and closes after 0.4 seconds. Figure 2 shows voltage and current waveforms for the transformer primary and secondary windings. The simulation was run and plotted for a duration of 1-second at 5 microsecond intervals. The gate pulses were blocked for the first 0.05 seconds to allow the DC source to ramp up and the capacitor to charge. See Figure 3 for a closer look at the waveform. The increase in current flow observed at time 0.4 seconds indicates connection of the utility system. In Figure 4, at the end of the run, the power factor has returned to nearly unity.

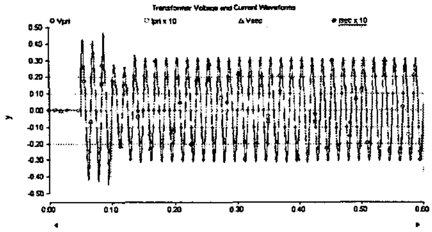

Figure2 - Transformer VI Waveforms

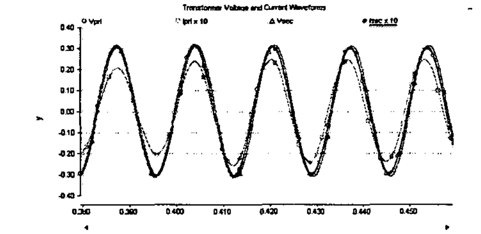

Figure3 - Detail of Transformer VI Waveforms

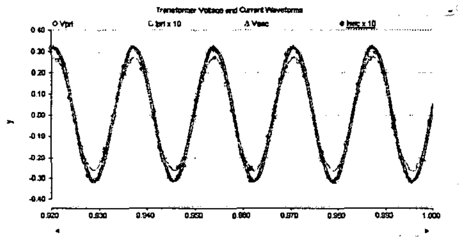

Figure4- End of Run Transformer VI Waveforms

2.1 Description of Control System

For the sake of simplicity, the gate-drive control system was implemented using bi-polar sinusoidal pulse-width modulation (SPWM). Figure 5 shows the voltage magnitude and phase controls were implemented using PSCAD's Continuous System Model Functions (CSMF).

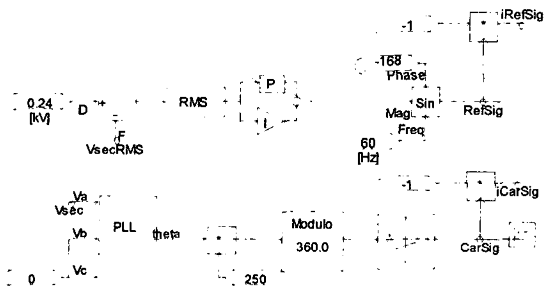

Figure5-PWM Reference & Carrier Signal Controls

The controls for this model incorporate PSCAD's Master Library models of a PI controller and a phase locked loop, plus a "user defined" component called "Modulo" found in their extensive example circuits (see statcom_6pls_pwm.psc in the example files). An important note about using someone else's "user defined" components is that they don't appear in your Master Library you must add them to your User Library. However, if you don't have the source files, you can still copy the component from the .psc file into your model as long as a copy of that .psc file is already open in PSCAD the next time you open your own model.

The PI controller in Figure 5 feeds an AM/FM/PM (Sine) Function to generate the PWM reference signal. A -168 degree offset was added to the reference signal to synchronize with the initial utility connection at time 0.4 seconds. The PI controller controls the inverter voltage to maintain the RMS voltage at the transformer secondary, while the PLL keeps the phase synchronized in the presence of a utility connection. A method of phase synchronization was implemented in this model, in which the PLL is used to generate the carrier signal [2]. The PLL component was originally designed for a 3-phase input, but according to the Help [3], only phase A is needed, so the B and C phase inputs were set to zero in this model. Following the PLL block is a multiplication block that acts, in conjunction with the Modulo function [2], to scale the frequency of the output (250 times 60, or 15,000 Hz). After the Modulo function changes the waveform back into a ramping function at the desired frequency, the non-linear transform characteristic changes the signal into a triangular waveform with peaks of +1 and -1.

2.2 Interpolated Gate-Firing Pulses

This model also takes advantage of PSCAD's interpolated firing pulse option, which provides improved simulation results by preventing errors from being introduced when switches fire between time simulation steps [4], [5]. This is accomplished by PSCAD's "Interpolated Firing Pulse Generator", found in the HVDC section of the Master Library. Figure 6 shows the gate pulse control schematic, including the time delay to block gate pulses on startup. As you can see from Figure 6, each gate pulse is actually a two value array; the first element gives the actual gate pulse (0 or 1), while the second element contains information about the interpolated switching instants. The interpolation algorithm is optional for each power electronic switch, and can be disabled in the switch parameters. However, one advantage is that it provides much better simulations especially at larger time steps. For example, the voltage, current waveforms and harmonic spectra of an interpolated simulation at a time step of 50 microseconds are equivalent to the non-interpolated case at 5 microseconds [6]. The other advantage is that fictitious snubbers are not needed in the simulation to prevent chatter caused by the trapezoidal integration solution method of the software [8].

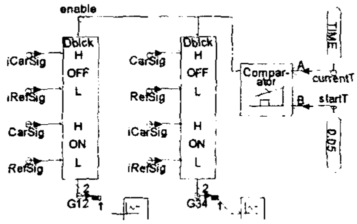

Figure6 - Gate-Firing Pulse Generators

The IGBT switches require both a turn on and turn off pulse, so the inverted reference and carrier signals are used for the off pulse. With this control scheme, switch pair 1,2 is on when 3,4 is off and vice versa (bi-polar PWM). The carrier and reference signals and the resulting gate pulses are shown in Figure 7.

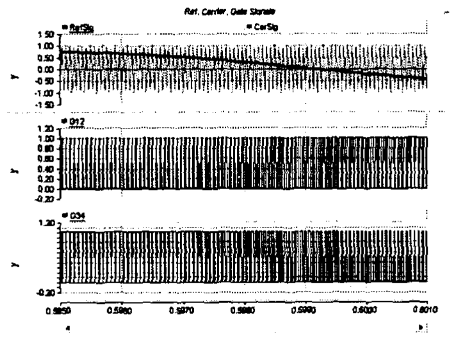

Figure7 - Reference, Carrier, and Gate Signals

2.3 Tuning the Controls

The controls were tuned using PSCAD's push-button controls (variable input sliders, see Figure 8). The resulting step change for the arrows is easily adjusted and/or the values can be entered via the keyboard. Note that PSCAD's PLL uses a gain factor for its integral adjustment, while the PI controller uses a time constant (in seconds) for its integral adjustment

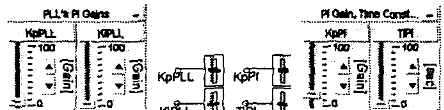

Figure8 - PLL and PI Controller Tuning

2.4 FFT analysis implementation in PSCAD

In this section, PSCAD's Online Frequency Scanner for Fast Fourier Transform (FFT, see Figure 9) is utilized for a demonstration of PSCAD's frequency-domain analysis capabilities.

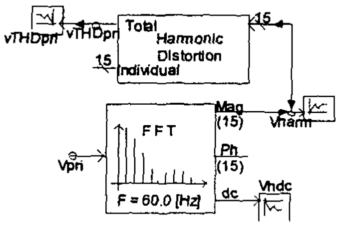

Figure9 - FFT and THD Components, v4.1

The FFT input can be any signal and the output is given in two multi-dimensional arrays (magnitude and phase) plus a single scalar (DC component). The number of harmonics desired for calculation is determined by the user, given the following four options: 7, 15, 31, 63. The output arrays can be viewed directly (via an output channel, see Figure 10, top and bottom graphs) and/or fed to PSCAD's Harmonic Distortion component for THD calculation, as shown in Figure 9. Some output waveforms from the inverter system are given in Figure 10. Current harmonics at steady state with grid connection do not exceed 1.5% THD, and voltage doesn't exceed 0.8% THD on the primary and 0.2% on the secondary.

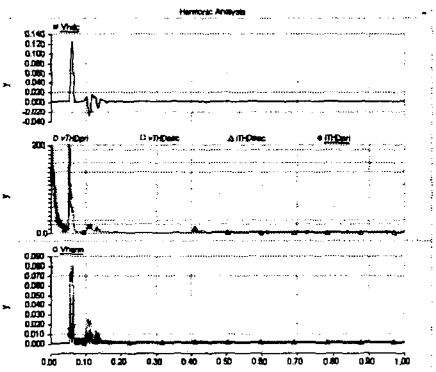

Figure10 - Harmonic Analysis, v4.1

With PSCAD v4.1, we can also easily view a signal's harmonic spectrum while the simulation is running using a meter-style object called a Polymeter (see Figure 11). It was captured by pausing the simulation and stepping to time 0.054705 seconds where harmonics were high.

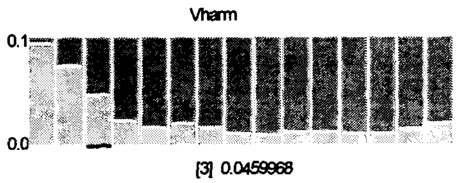

Figure11 - Harmonic Spectrum Polymeter, v4.1

With earlier PSCAD versions (pre 4.1), displaying the output of the FFT component requires a little more effort. The 7, 15, 31, or 63 element output arrays must be tapped for each individual signal and linked to an output channel before they can be viewed in PSCAD (see Figure 12). This is quite tedious and waste of space for a 63 element array!

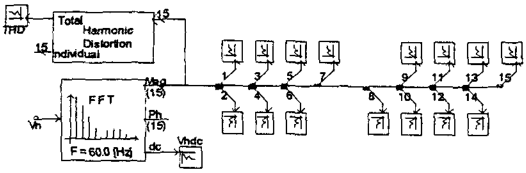

Figure12- FFT Display Requirements, v4.0

In PSCAD versions 2 and 3, there is no way to view a signal's harmonic spectrum (magnitude versus frequency) within PSCAD, however, using the XY plotting capabilities of PSCAD v4.0 and newer, we can plot one signal versus another. Using this capability, we have implemented a work-around for v4.0 to display a harmonic spectrum for a signal at steady state (see Figure 13).

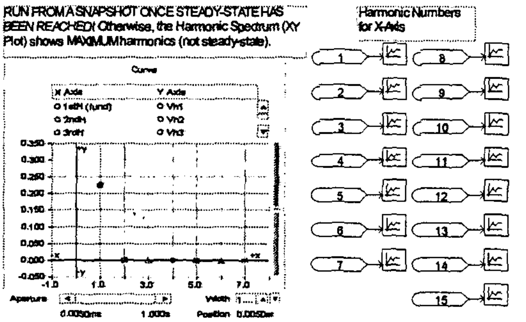

Figure13- Harmonic Spectrum Work-around, v4.0

The glyph symbols indicate harmonic magnitude at each multiple of fundamental frequency (horizontal X-axis). Scaling the XY plot is a little tricky (check that "Maintain Aspect Ratio" is NOT selected), but the work-around does its job.

One note of caution: the harmonic spectrum generated in this way is useful for circuits at steady state. Figure 13 was generated after taking a snapshot at 1 second and then, starting from this snapshot, running for another 1 second. If steady state is not achieved, the XY plot shows all values of harmonics the occurred during the run superimposed on each other (see Figure 14) with no way to determine which is first or last. However, this is one way to see the peak harmonics in a run if you don't have v4.1

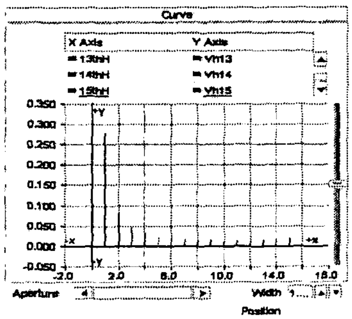

Figure14 - Harmonic Spectrum Maximums, v4.0

One final note on this work-around: if you copy this FFT with meters and graphs to another page, you will have to remove and re-add ALL meter and graph curves (this is tedious). The best advice is, of course, upgrade; v4.1 has some very nice, user-friendly features that you will wonder how you ever lived without.

3. Conclusion

The purpose of this paper was to describe and demonstrate how a utility-connected power electronic DC-AC inverter for photovoltaic or fuel-cell applications can be well modeled using PSCAD/EMTDC software. In this paper, a single-phase IGBT inverter was modeled using bi-polar SPWM. Simple voltage magnitude and phase controls were implemented and explained. The controls incorporated PSCAD's Master Library models of PI and PLL controllers, plus a "user defined" component called Modulo (found in their extensive collection of example circuits). The circuit model also illustrated PSCAD's interpolated firing pulse option, which provides improved simulation results by preventing errors from being introduced when switches fire between time simulation steps. Additionally, PSCAD's Online Frequency Scanner for FFT was utilized for a demonstration of PSCAD's frequency-domain analysis capabilities

[References]

[1] "An LC Filter Design Method for Single Phase PWM Inverters", P.A. Dahono, et. al., 1995 IEEE

[2] "Modeling and Analysis of a 1.7 Mva SMES based Sag Protector", S. Santoso, et. al., 2001 IPST

[3] PSCAD 4.03 On line Help, "Three Phase PI-Controlled Phase Locked Loop" and "TVEKT3 Subroutine"

[4] PSCAD 4.03 On line Help, "Interpolation and Switching"

[5] "A Fully Interpolated Controls Library for Electromagnetic Transients Simulation of Power Electronic Systems", A.M. Gole, et. al., June 2001, IPST, Brazil

[6] "Power Electronics Spark New Simulation Challenges", O. Nayak, et. al., October 2002, IEEE Computer Applications in Power

[7] "Modeling and Analysis of Custom Power Systems by PSCAD/EMTDC", Olimpo Anaya-Lara and E. Acha, 2002 IEEE

[8] "Guidelines for Modeling Power Electronics in Electric Power Engineering Applications", A.M. Gole, et. al, January 1997, IEEE Transactions on Power Delivery.

[9] 분산전원의 모델링 및 계통 연계에 따른 전력품질의 분석 (Modeling and Analysis of Power Quality on Power System Interconnected Distributed Generation), 박지웅 (J.W. Pak), 2003, 성균관대학교 석사논문 (SungKyunKwan University Master's degree thesis)