Comparative Study of Various PWM methodologies for Grid connected Inverter for RES Application

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***Abstract*— The installation of Distributed Generation (DG) systems leads to harmonic distortions, unequal power sharing among the host feeders and system voltage and frequency imbalances. These power quality issues arise mostly when main grid interacts with DG systems or when they operate in islanded mode. Henceforth, with a two-step approach as this paper presents, proper frequency and voltage control of DG systems is acquired to solve these problems. In the first step, a comparison in terms of harmonic content is performed between Sinusoidal Pulse-Width-Modulation (SPWM), Hysteresis Pulse-Width-Modulation (HPWM) and Space Vector Pulse-Width-Modulation (SVPWM) techniques for interface inverters in distributed configuration. Secondly, an improved droop control method is implemented in order to regulate voltage and frequency as a function of customized droop equations. Validation of design method and parametric analysis of results is provided with the help of simulations.**

***Index Terms*— SPWM; HPWM; SVPWM.**

I. Introduction

The incorporation and integration of non-conventional or renewable energy sources in the grid results in a new term called “Distributed Generation (DG)” which stands for on-site generation in electricity markets [1]. “The distributed generation system is an internet of power sources combined together to perform in an efficient, reliable and flexible manner” [1]. “DG system components comprise of micro-sources (fuel cells, solar, wind, etc.), loads, storage systems, control and communication circuitry and grid-interactive inverters. Balancing demand and supply is partly done by using local storage i.e. batteries, directly tied to the DC grid” [2]. The evolution of distributed generation is a result of number of factors related to regular remote utility generation and transmission system such as aging, deterioration costs, and energy loses over long power transmission network. It is believed that distributed generation is capable of avoiding the need for the development of new transmission and distribution lines. At the minimum, the grid has to be available as a backup supply so as to increase the system reliability at the same time [3].

The relation between distributed generation and power quality is ambiguous but important. On one hand, some experts stress the negative effect on power quality by the installation of DG systems, while others emphasize its restorative effects for power quality complications in power networks [4]. For example, in areas where the utility grid is weak and voltage support is difficult, DG can contribute to a rise of voltage in the network. Nevertheless, distributed generators introduce harmonics into the power system. The types and severity of harmonics depend on the power converter technology and interconnection configuration.

This manuscript presents a simple yet seamless and flexible approach to solve the problem of harmonics in DGs, keeping into account proper power sharing in case of multiple sources and loads. A parametric analysis of sinusoidal pulse width modulation (SPWM) and space vector pulse width modulation (SVPWM) for interface inverters in distributed configuration with the grid has been presented. This analysis provides the basis of optimum compensation of harmonics to enhance power quality at system level. The combined system effect defines new paradigms of improved DG systems in terms of performance, efficiency and economics.

II. DISTRIBUTED RESOURCES

"Distributed resources such as micro-turbines, fuel cells, and photovoltaic arrays are small relative to system capacity, but the smaller sizes are much more likely to achieve significant penetration levels. It is therefore reasonable to address the question of allowable penetration by assuming a harmonic injection at the limit levels specified" [5]. The motivation behind the work in this paper is the development of flexible, seamless and improved approaches for micro-grid inverters and their synchronization with the utility grid and loads and development of new and improved techniques to meet power quality benchmarks and reliability standards. Harmonic mitigation approaches of [6]-[8] are based on making the DG units of a power distribution system replicate a resistance at harmonic frequencies. For micro-grid operation, fundamental control strategies have been defined in [9]-[10] with regards to harmonic compensation and power quality improvement.

The control method described in [11] uses a modular approach in order to control power flow and share of a micro-grid system with mechanism to compensate the voltage harmonics. This work is based on the same methodology for potentially using the space vector pulse width modulation for micro-grid inverters tied to the utility grid in distributed generation configuration. A parametric analysis of both SPWM and SVPWM based micro-grid inverters has been performed to show a solution oriented comparative approach for power quality enhancement. After the performance evaluation and comparison between both the techniques, appropriate conclusions have been made. The results best suited to the solution of power quality issues have been discussed in detail in order to highlight the main contribution of this paper.

III. POWER QUALITY IMPROVEMENT

The combination of technology innovation in power electronics, electricity deregulation, economics, customer value, and energy demand is causing the electric power industry to shift from a few large concentrated generation centers to a more distributed and dispersed power generation infrastructure [12]. Power quality issues in DG systems are mainly due to the high penetration level of harmonics that disrupt voltage profile of the system. Harmonic problems are tied with the switching device technology, the nature of the characteristic harmonics, equipment ratings, and loading conditions of the host distribution feeder. Under the present framework of IEEE 519-1992, the supplier of electricity is responsible for the quality of the voltage supplied. The end-user is responsible for limiting harmonic current injections based on the size of the end-use load relative to the capacity of the system [13].

Power electronic inverters are a major concern over which the possible harmonic current contributions they may make to the utility system. To some extent, this concern arises due to the use of Silicon Controlled Rectifier (SCR) technology based inverters. They are line-commutated and inject high levels of harmonic current through the distributed system. Most types of new inverter topologies are based on Insulated Gate Bipolar Transistors (IGBTs) that use pulse-width-modulation (PWM) technology to generate the injected "sine" wave. They are capable of generating much cleaner output and normally meet the standards set by IEEE 519-1992 [13].

"From the harmonic modeling and simulation standpoint, a distributed generator is usually a converter-inverter type unit and can therefore be treated as a non-linear load injecting harmonics into the distribution feeder" [11]. Harmonics in output line-line voltage of three phase voltage source inverters can be calculated by the following equation.

Harmonics arise from the inverter switching as well as due to the transitions of micro-grid between grid-connected and islanded modes. They must be compensated in order to get the improved voltage profile at the loads for power quality enhancement. Moreover, during the gird-connected operation, depending on the design of the generator windings (pitch of the coils), core non-linearity, grounding and other factors, there can be significant harmonics present in the system [14]. Triple harmonics are additive in the neutral; and the third harmonic is often the most prevalent. Synchronous generators are often specified with a 2/3 pitch for the windings as much less third harmonic is produced than those with other pitches. Unfortunately a 2/3 pitch machine has a lower impedance to third harmonic and may cause more harmonic current to flow from other sources connected in parallel with it [14]. The feeder penetration of harmonics is limited by the grounding arrangement of the generator and step-up transformer.

IV. TOPOLOGY FOR POWER QUALITY

The DG system under consideration consists of a utility grid with bulk generation from a large generator rated at 11KV and two micro-grids connected through a Point of Common Coupling (PCC) to the utility grid and distributed loads. Micro-grids have DC sources rated at 380-400V DC. Circuit breakers (reclosers) are installed for interfacing micro-grids with the utility grid forming different zones. In grid-connected mode, power is fed to loads through the main grid. In case of island (fault or unavailability of the grid), power demands are fulfilled through micro-grids. This adds flexibility, efficiency, and reliability to the system. Fig. 1 shows the developed system model.

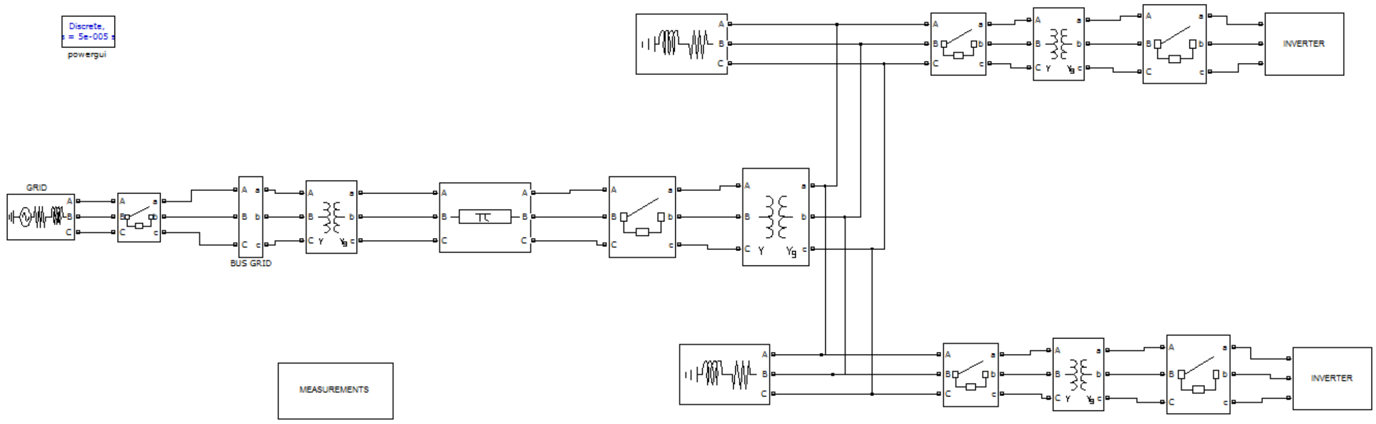

Fig. 1. MATLAB model of DG system under consideration

The high level schematics of system under consideration are shown above. This system has been further categorized into subsystems for modeling the distributed generators micro-sources and voltage source inverters. The subsystem provides a voltage and power output at the point of common coupling with the main grid. There are two types of controls for this system. One is supervisory control for the grid and other is distributed control for inverters [15]. Accurate power sharing is determined by more familiar droop control. Subsystems for SPWM and SVPWM are shown in fig. 2 and 3 respectively.

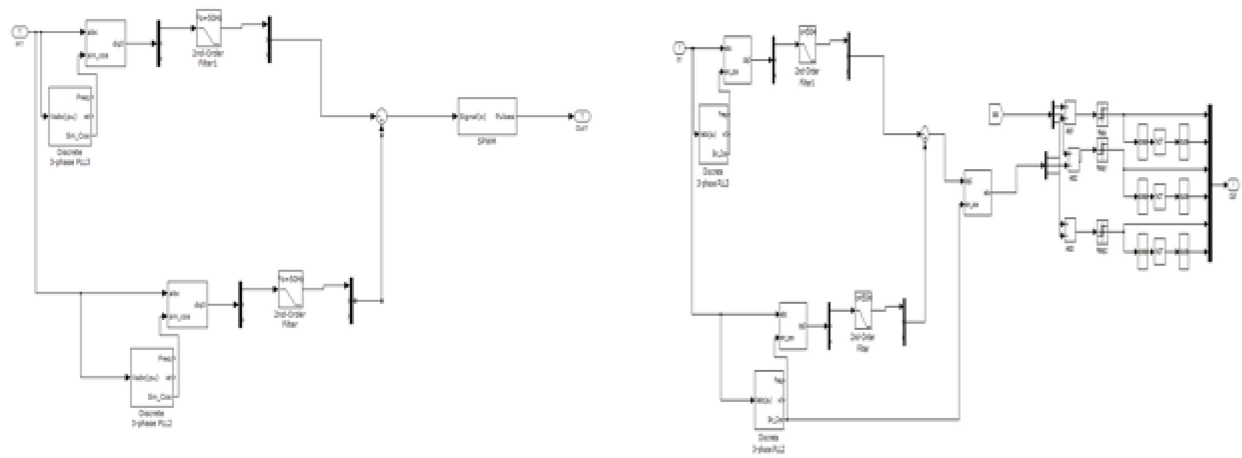

Fig. 2. Subsystem model for SPWM & HPWM based micro-grid inverter

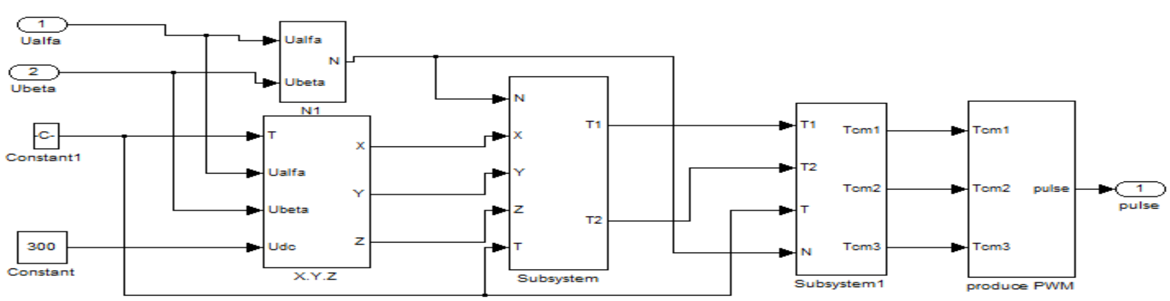

Fig. 3. Subsystem model for SVPWM based micro-grid inverter

For power sharing using droop control, it is evidenced that active power-voltage (P-V) droop and reactive power-angle (Q-ω) boost functions are the true measure of active and reactive power sharing when the network is considered to be low voltage. These functions can be modeled by the following set of equations

$$\omega = \omega o + kq(Qo - Q) \quad (4.1)$$

$$E = Eo - kp(Po - P) \quad (4.2)$$

where,
k_p: voltage droop coefficient
k_q: frequency boost coefficient
Ȧ$_o$: nominal frequency
V_o: rated phase voltage magnitude
P: real power output of micro-grid inverter
P_o: nominal real power output
Q: reactive power output of micro-grid inverter
Q_o: nominal reactive power output

V. SIMULATION RESULTS

The three-phase filter used is rated at 500 Hz cut-off frequency with inductance 150 mH and capacitive power 3 *KVAR* and shown in fig. 4. The filter is installed at the output of three-phase voltage source inverter forming a DG or a micro-grid subsystem. The harmonic compensation is done by the combined system operation [16] of power filter, modulation schemes and control algorithm. The proposed system uses both sinusoidal and space-vector PWM techniques for micro-grid inverters. Results are shown in following subsections.

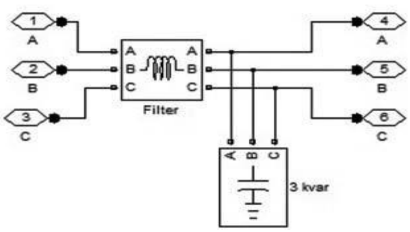

Fig. 4. Three-phase filter used at inverter-grid-load interface

A. *Hysterisis Pulse Width Modulation based Micro-grid Inverter:*

SPWM uses many more square waves (at a much higher frequency) to mimic the shape of a sine wave. Sinusoidal PWM technique, gives an output wave that is very easy to filter into a pure sine wave because very little energy has to be absorbed and later released during the cycles of the higher frequency signal. This means a much cleaner output with smaller inductors and capacitors can be obtained. Simulation parameters used for micro-grid inverter are shown in table 1. Voltage and current waveforms including line-line voltage, line-neutral voltages and phase currents of SPWM based micro-grid inverter are shown in fig. 5.

DC-Link Voltage	Vdc=380 V
Fundamental Frequency	f=50 Hz
Switching Frequency	fs=1 MHz
Sampling Time	Tz=10^{-6} sec
Modulation Index	a=0.85
Filter	2nd Order Low Pass
Cut-off Frequency	fo=500 Hz

Table 1. Simulation parameters for SPWM based micro-grid inverter

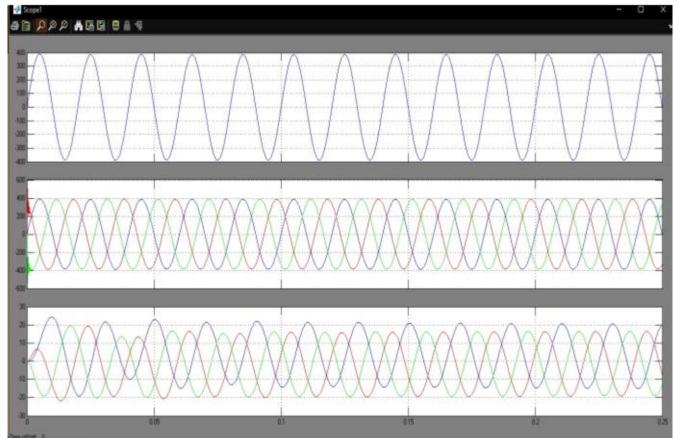

Fig. 5. Line-line voltage, Line-neutral voltages and phase currents of SPWM based micro-grid inverter

FFT analysis of these waveform shows that very less amount of harmonic content is present. Total Harmonic Distortion (THD) analysis shows that micro-sources with control are able to reduce the harmonic content below 5% which is in accordance with the IEEE allowed limit.

B. *Space Vector Pulse Width Modulation based Micro-grid Inverter:*

Space vector pulse-width-modulation (SVPWM) is used for micro-grid inverters because of its fast real-time response, low harmonic content and high efficiency. It is a digital modulating technique where the objective is to generate PWM load line voltages that are in average equal to reference load line voltages [17].

DC-Link Voltage	Vdc=400V
Fundamental Frequency	f=60Hz
Switching Frequency	fz=10kHz
Sampling Time	Tz=10msec
Modulation Index	a=0.85
Filter	2nd Order Low Pass
Cut-off Frequency	fo=500Hz

Table 2. Simulation parameters for SVPWM based micro-grid inverter

Simulation parameters for SVPWM based micro-grid inverter are used as in table 2. Three-phase voltages injected by space vector modulation based micro-grid inverter and subsystem currents are sown in in fig. 6. It can been witnessed that with proposed design, smooth waveforms lead to power dense grid operation as desired.

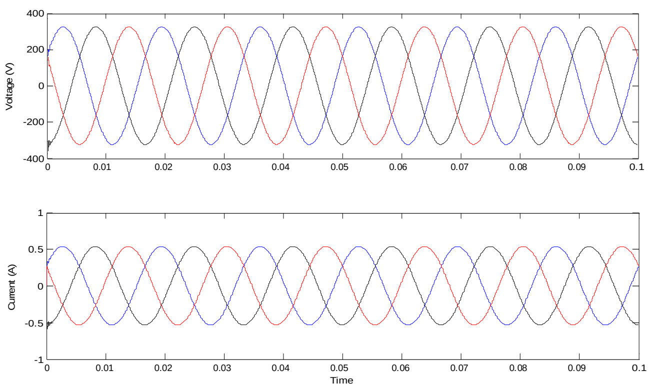

Fig. 6. Subsystem voltages and currents with SVPWM based micro-grid inverter

FFT analysis of output waveforms to check THD shows that proposed method is quite effective in harmonic mitigation and yields smooth and power dense DG system operation. Moreover, in comparison with previously reported results for this problem is 1.39%.

A formal performance evaluation and parametric analysis of the results is provided in fig. 7. It shows the power quality improvement with reduction of harmonic content in the system through different strategies applied to micro-grid including PQ control, sinusoidal pulse width modulation, Hysteresis pulse width modulation, space vector modulation, droop control and additional power filters.

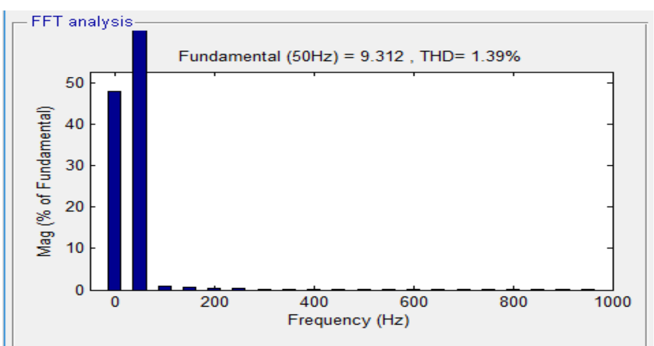

Fig. 7. Parametric analysis of results for power quality improvement through different strategies applied to micro-grid

CONCLUSIONS

The control of a DG system has been improved with efficiency, high reliability and power density and less complexity. A seamless and flexible real-time solution has been proposed to take care of key issues related to power quality. Parametric results highlight the effectiveness and validation of the approach in which system level power quality has been improved. The main contribution of this paper is to sum up different approaches proposed to take care of power quality issues in distributed generation systems and to provide a comparison between up-to-date approaches using various simulations for combined system. The system complexity with communication and sensing and addition of dimensions remain as a future challenge.

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