Application of Sigma-Delta Modulation in a Modified Multifunction Current Controller for Inverter-Based Distributed Generation

Abstract—**There are many consumers and equipments in Distributed Generation (DG) systems and distributed networks which have rapid changes in the reactive power consumption. These changes can cause large-amplitude variations in the load-side voltage and can influence on the operation of other power consumers which are fed from Point of Common Coupling (PCC). In this paper a current control strategy for inverters based on Sigma Delta Modulation (SDM) which are interfacing in DG is proposed. The proposed interface is called Sigma-Delta based Current Controlled Voltage Source Inverter (ΣΔ_CC_VSI) and controls active and reactive power independently with fast voltage regulation. The proposed ΣΔ_CC_VSI reduces the harmonics amplitude variations of the unfiltered voltage. So has effect on ElectroMagnetic Interference (EMI) reduction which is important for some consumers.**

I. INTRODUCTION

DG system is defined as an electric power source that connected directly to the distribution network or on the customer into the meter. This source can be a co-generation system with micro-turbine, fuel cell generation systems or any kind of renewable energy sources.

The integration of the DG with the utility distribution network offers a number of technical, environmental and economic benefits. It also gives a great opportunity for distribution utilities to improve the performance of networks by reducing its losses [1]. The technical challenges associated with the DG can be subdivided into three categories:

- The system interface to the grid.
- Operation and control of the DG.
- Planning and design.

This paper focuses on the first and second categories and aims to investigate a control system. The control system controls active and reactive power of interface system separately and independently. In addition, the control system aims to fast voltage regulation of AC bus for power quality needs.

Reactive power compensation is an important issue in the control of distribution systems. Reactive current increases the distribution system losses, reduces the system power factor, shrinks the active power capability and can cause large-amplitude variations in the load-side voltage. Moreover, rapid changes in the reactive power consumption of large loads can cause voltage amplitude oscillations (e.g., flicker in the case of arc furnaces). This might lead to a change in the electric system real power demand resulting in power oscillations [2].

In power electronics, attention was attracted to SDM when resonant dc link inverters were discussed [2]. Even before that, Delta Modulation based current-regulators, which follow a similar principle of operation and have a very similar performance, were proposed for conventional voltage source inverters [4-5]. A profound performance analysis of SDM controlled inverters, plus approximations for some space-vector based varieties, was reported in [5].

The most important characteristics of SDM and related strategies are:

- Switching instants of the devices (on or off) are synchronized to a clock with frequency f_c,
- Variable switching frequency, at maximum half the clock frequency $f_c/2$,
- Widespread output spectra with some content of low-order and sub-harmonics,
- Very simple implementation with only a few digital or analog-digital components.

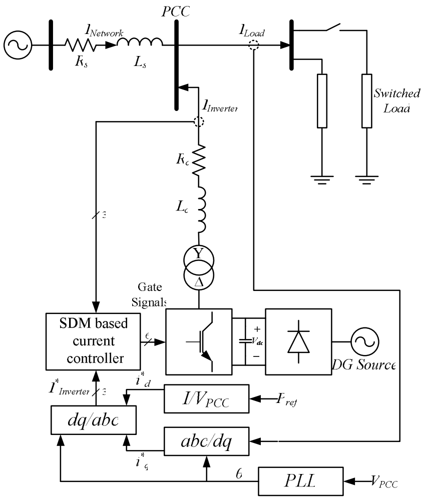
In general with PWM scheme, noise peak spectra appears at every whole number of carrier frequency and this property causes bad influence on the electronic information, telecommunication and medical equipments which are abundantly fed in distribution networks [6].

Due to aforementioned points, SDM or DM is widely used as a modulator or controller (like in sliding mode control) in power electronics devices like power factor corrections, inverters, DC/DC converters [7].

According to mentioned advantages, it seems that application of SDM (or DM) based inverters as an interface for DG system is useful. Thus, this paper proposes a current control strategy for VSI which separates the active and reactive power control and apply SDM strategy as current control loop. The proposed interface for DG systems is called ΣΔ based Current Controlled Voltage Source Inverter (ΣΔ_CC_VSI). Operation of proposed control is simulated by PSCAD/EMTDC and its results compared with the results of [2] to verify it. Comparison of simulation results with the same configuration in [2] shows that the proposed current control strategy can reduce the harmonic of output voltage of VSI rather than [2] results.

II. PROPOSED CURRENT CONTROL STRATEGY

Fig. 1 shows the proposed current control strategy associated with its control blocks and connected to a typical power system. The components of the system are: the shunt converter which gets its DC input voltage from a rectified DG through a smoothing capacitor C, the transformer and the current smoothing filter. The converter manages the amount of $I_{Inverter}$ injected to the utility. Utilizing *dq* transformation rotating at the supply frequency ω, the load current I_L is converted from the three phase coordinates to synchronously rotating frame given by equation (1), where θ is the instantaneous angle of the PCC voltage vector. It is obtained from Phase Locked Loop (PLL) circuit [8].



$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} \cos(\theta) & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ -\sin(\theta) & -\sin(\theta - 2\pi/3) & -\sin(\theta + 2\pi/3) \\ \sqrt{1/2} & \sqrt{1/2} & \sqrt{1/2} \end{bmatrix} \times \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

Fig. 1. Detailed component of proposed ΣΔ_CC_VSI

III. SDM TECHNIQUE APPLIED IN ΣΔ_CC_VSI

SDM is categorized in some category which the simplest form of it, is shown in Fig. 2. i_{ic}^* is the input signal, *u(t)* is the integrator state, and *y(t)* is the latch output. The comparator is thought of as a quantizer whose output *q(u(t))* is ±1 according to the sign of the integrator state *u(t)*. The latch samples the comparator or quantizer output *q(u(t))* at the sampling frequency f_c and holds that value until the next sampling instant.

Intuitively, the SDM uses feedback to lock onto a band-limited input signal *x(t)*. As explained in [9], "Unless the input signal *x(t)* exactly equals one of the discrete quantizer output levels, a tracking error results. The integrator accumulates the tracking error over time and the quantizer and latch feedback a value that will minimize the accumulated tracking error. Thus, the quantizer output *y(t)* toggles about the input signal *x(t)* so that the average quantizer output is approximately equal to the average of the input."

To illustrate how a power electronic circuit can be embedded in a SDM, consider the modulator for the half bridge converter shown in Fig. 2. In this arrangement the gating circuitry and half-bridge are embedded into the loop following the latch in Fig. 2. The comparator and latch set the switch state for each sampling period according to the sign of the comparator input *u(t)* at the sampling instant. The switch state impresses the voltage $\pm V_o$ on the output, *y(t)*. Since Figs. 3 and 4 are different implementations of the same overall quantizing and latch functions, the corresponding modulators have identical behavior. Thus, by taking the input signal *x(t)* to be the desired output voltage, the actual output voltage *y(t)* will approximate the desired output voltage. As will be seen, this approximation can be improved by generalizing the integrator in Fig. 2 to a linear filter or by increasing the sampling rate f_c.

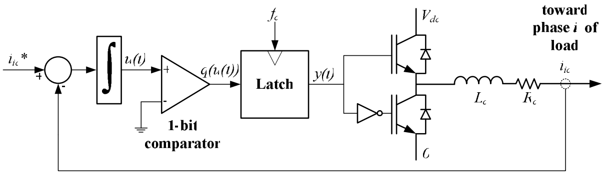


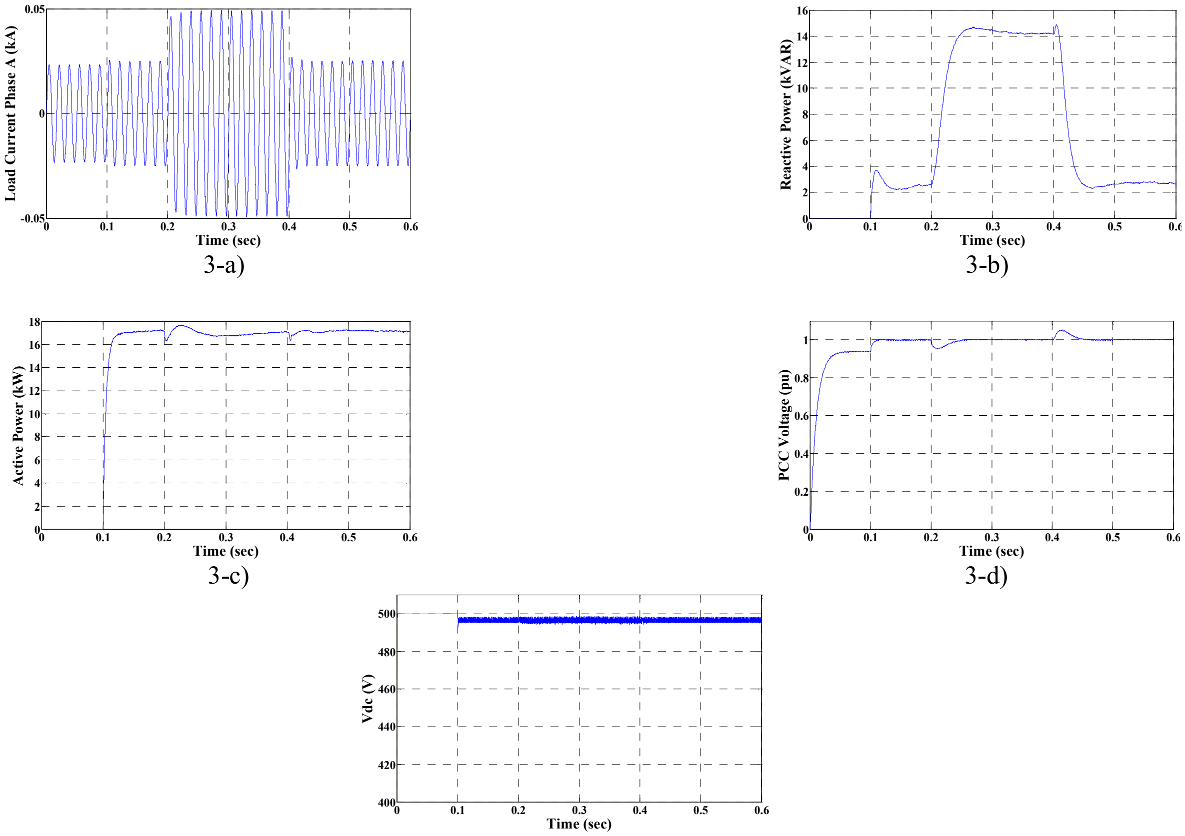
Fig. 2. ΣΔ Current Controller technique
(inverter embedded in SDM loop)

IV. SIMULATION RESULTS

The performance of the proposed ΣΔ_CC_VSI is evaluated by computer simulation using PSCAD/EMTDC. The parameters of the system under study has been given in appendix of [2] and EMTDC time step has been set at 10 (µsec). In addition the sampling rate (f_c) has been set at 20 (kHZ). The following simulation results illustrate the operation of ΣΔ_CC_VSI in reactive power compensation mode. The First task of this simulation is to evaluate the performance of the proposed ΣΔ_CC_VSI in compensating the reactive power at the PCC under sudden load changing condition, while retain the active power at its reference value. Fig. 3, shows the dynamic response of the proposed ΣΔ_CC_VSI when started at t=0.1 (sec) and when high load (110% of the connected load) is switched at t=0.2 (sec), and then removed at t=0.4 (sec), as shown in Fig. 3-a. It is clear from Fig. 3-b that the ΣΔ_CC_VSI succeeded in tracking and compensating the reactive power demand of the load with fast dynamics and with minimum overshoot. Fig. 3-c shows that the active power supplied from ΣΔ_CC_VSI is almost constant and equal to its input command value (17 KW) from the control circuit. It is clear from Fig. 3-b and 5-c that the control of active and reactive power is decoupled and each of them is independent on the other. A low change observed in active power at t=0.1 (sec) and t=0.4 (sec) instantaneous is due to a little dependence in active and reactive power.

In addition, Fig. 3-d shows the effect of ΣΔ_CC_VSI on the voltage at the PCC. Introducing ΣΔ_CC_VSI improves the per unit voltage at PCC from 0.9 (pu) to 1.0 (pu). In addition, when the load disturbance occurred, ΣΔ_CC_VSI shows that it is still enhancing the voltage level with a little decrement, which results due to the uncompensated active current component of the load disturbance. Finally, Fig. 3-e shows the DC bus voltage, which is clearly constant.

In full paper version the additional results has been shown. According to those results, the harmonics amplitude variations of proposed control strategy are lower than control strategy of [2]. This reduction is due to use of SDM instead of Hysteresis Current Control which is used in [2].



3-a)

3-b)

3-c)

3-d)

3-e)

Fig. 3. Dynamic response of the proposed ΣΔ_CC_VSI due to sudden load change a) load current b) reactive power variations c) reactive power variations d) VPCC variations e) DC bus voltage

V. CONCLUSION

DG systems and distributed networks have many consumers and equipments which have rapid changes in the reactive power consumption. These changes can cause large-amplitude variations in the load-side voltage and can influence on the other consumers which are fed from PCC (like: electronic information, telecommunication and medical equipments).

To mitigate power quality problems at PCC, current controlled VSI was selected for its fast dynamic response, accurate performance, ease of implementation and its inherent closed loop control. In this paper a current control strategy for inverters interfacing in DG was proposed based on SDM.

The proposed interface (ΣΔ_CC_VSI) controls the active and reactive power independently with fast dynamic response of system currents. The proposed ΣΔ_CC_VSI reduced the harmonics amplitude variations of the unfiltered voltage and THD of voltage and current. Therefore had effect on EMI reduction which is important for some consumers like medical equipments.

Simulation results have been shown that the proposed inverter interface has multifunction operation. So, there is no requirement to active power filter for compensating the reactive power and fast voltage regulation. In addition the proposed inverter interface provides the active power requirement of load.

In future work for verifying the operation of proposed inverter interface, experimental results will use instead of comparison with [2] results.

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