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POWER QUALITY IMPROVEMENT FOR MULTIPLE OUTPUTS SWITCHED MODE POWER SUPPLY BASED ON BRIDGELESS CONVERTER

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ABSTRACTS

Power electronic converters are commonly used for interfacing distributed generation (DG) systems to the electrical power network. This paper deals with a single-phase inverter for DG systems requiring power quality features, such as harmonic and reactive power compensation for grid-connected operation. The idea is to integrate the DG unit functions with shunt active power filter capabilities. With this approach, the inverter controls the active power flow from the renewable energy source to the grid and also performs the nonlinear load current harmonic compensation by keeping the grid current almost sinusoidal. The control scheme employs a current reference generator based on sinusoidal signal integrator and instantaneous reactive power (IRP) theory together with a dedicated repetitive current controller. Experimental results obtained on a 4-kVA inverter prototype demonstrate the feasibility of the proposed solution. Comparing with conventional topologies the proposed topology reduces conduction losses and improves power quality. The performance evaluation of multiple output SMPS is done under steady state, varying input voltage. The performance of this SMPS is simulated in MATLAB/simulink environment.

INTRODUCTION

RECENTLY, due to the high price of oil and the concern for the environment, renewable energy is in the limelight. This scenario has stimulated the development of alternative power sources such as photovoltaic panels, wind turbines and fuel cells. The distributed generation (DG) concept emerged as a way to integrate different power plants, increasing the DG owner's reliability, reducing emissions, and providing additional power quality benefits. The cost of the distribution power generation system using the renewable energies is on a falling trend and is expected to fall further as demand and production increase. The energy sources used in DG systems usually have different output characteristics, and for this reason, power electronic converters are employed to connect these energy sources to the grid, as shown in Fig. 1. The power electronic front-end converter is an inverter whose dc link is fed by an ac/dc converter or by a dc/dc converter, according with the DG source type. The commercial front-end inverters are designed to operate either as grid-connected or in island mode. In grid-connected mode, the voltage at the point of common coupling (PCC) is imposed by the grid; thus, the inverter must be current-controlled. When operated in island mode, the inverters are voltage-controlled, generating the output voltage at a specified amplitude and frequency.

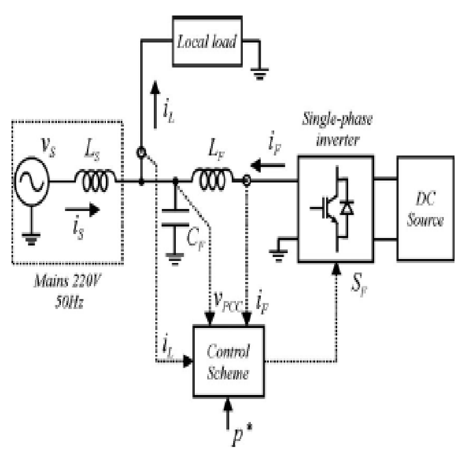


Fig.1. General Scheme of a DG unit connected to the grid.

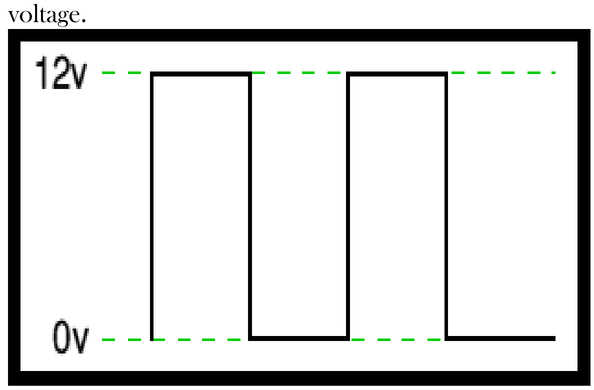
Coming to the grid-connected mode, almost all the commercial single-phase inverters for DG systems inject only active power to the grid, i.e., the reference current is computed from the reference active power p^* that must be generated. It is possible and can be convenient to integrate power quality functions by compensating the reactive power and the current harmonics drawn by specific local nonlinear loads (see Fig. 1). The single-phase inverter can acquire active filtering features just adding to its control software some dedicated blocks that are specific to shunt active power filter (APF). This paper proposes and validates an enhanced power quality control strategy for single-phase inverters used in DG systems. The idea is to integrate the DG unit functions with shunt APF capabilities. With the proposed approach, the inverter controls the active power flow from the energy source to the grid and also performs the compensation of reactive power and the nonlinear load current harmonics, keeping the grid current almost sinusoidal.

The integration of APF capability in single-phase inverters needs a particular attention since the control techniques (for example, to find the reference current) were developed for three phase APFs, and consequently, must be adapted for single-phase systems. The literature presents different solutions to compute the harmonic extraction task for single-phase APFs. The methods are classified in direct and indirect methods. The direct methods include the Fourier transform method, the instantaneous reactive power (IRP) theory and the synchronous reference frame (SRF) theory. On the other hand, the indirect methods include the use of enhanced phase-locked loop (EPLL) scheme or a controller such as proportional–integral (PI) to find the reference current. Among these solutions, the IRP and the SRF theories are the most addressed ones in the literature. These strategies were originally proposed for three-phase systems, but they can be adapted for single-phase systems due to their effectiveness. In three-phase systems, both IRP and SRF techniques operate in a reference system with two orthogonal axes ($\alpha\beta$ for IRP and dq for SRF). In single-phase systems, since only one-phase variable exists, it is necessary to create one “fictitious” or imaginary variable in which all frequencies are phase-shifted by 90 electrical degrees with respect to the original variable. With this procedure, a system with two orthogonal variables is created from a single variable, allowing the application of the IRP and SRF theories. However, the computation of the fictitious variable from the existing one is not a simple task since the nonlinear load current has a high harmonic content. The imaginary variables are calculated in by using the Hilbert transform. This method leads to a no causal system and cannot be directly implemented. However, it is possible to approximate the transformation through a finite-impulse response (FIR) filter, and in this case, some phase delays are introduced in the fictitious variable and implicitly in the inverter current reference. Alternatively, the computation of the reference current can be performed by using a sinusoidal signal integrator (SSI) along with the IRP theory. This approach has been originally proposed by the authors and allows obtaining without any delay the fictitious variables that are needed to apply the IRP theory or other techniques originally applied for three-phase systems. Moreover, the reference current computation is insensitive to grid voltage distortions. The authors in experimentally validated only the current harmonics compensation features of the strategy since the inverter has been operated only as an active filter.

This paper shows the complete experimental validation of the proposed method for all its features, i.e., active and reactive power generation along with current harmonics compensation. Moreover, the paper employs a dedicated inverter current control scheme based on a repetitive controller implemented with a FIR filter approach. With respect to previous repetitive control solutions, the one proposed by the authors allows halving the number of the FIR filter taps, making the implementation easier from the point of view of the computational effort.

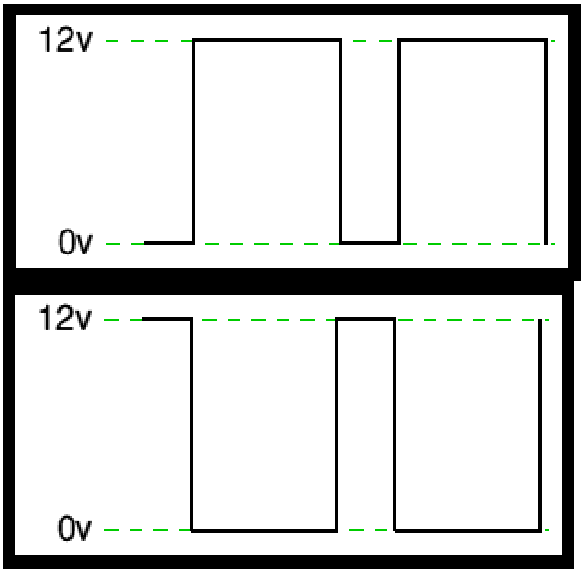
PULSE WIDTH MODULATION (PWM)

Pulse Width Modulation (PWM) is the most effective means to achieve constant voltage battery charging by switching the solar system controller’s power devices. When in PWM regulation, the current from the solar array tapers according to the battery’s condition and recharging needs Consider a waveform such as this: it is a voltage switching between 0v and 12v. It is fairly obvious that, since the voltage is at 12v for exactly as long as it is at 0v, then a 'suitable device' connected to its output will see the average voltage and think it is being fed 6v - exactly half of 12v. So by varying the width of the positive pulse - we can vary the 'average' voltage.



Similarly, if the switches keep the voltage at 12 for 3 times as long as at 0v, the average will be 3/4 of

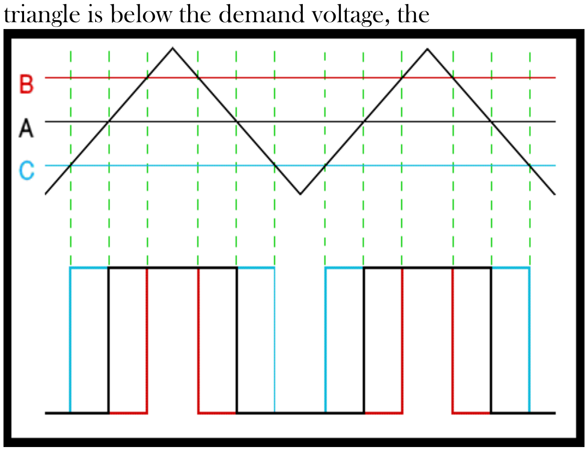
12v - or 9v, as shown below and if the output pulse of 12v lasts only 25% of the overall time, then the average is



By varying - or 'modulating' - the time that the output is at 12v (i.e. the width of the positive pulse) we can alter the average voltage. So we are doing 'pulse width modulation'. I said earlier that the output had to feed 'a suitable device'. A radio would not work from this: the radio would see 12v then 0v, and would probably not work properly. However a device such as a motor will respond to the average, so PWM is a natural for motor control.

Pulse Width modulator

So, how do we generate a PWM waveform? It's actually very easy, there are circuits available in the TEC site. First you generate a triangle waveform as shown in the diagram below. You compare this with a d.c voltage, which you adjust to control the ratio of on to off time that you require. When the triangle is above the 'demand' voltage, the output goes high. When the triangle is below the demand voltage, the



When the demand speed it in the middle (A) you get a 50:50 output, as in black. Half the time the output is high and half the time it is low. Fortunately, there is an IC (Integrated circuit) called a comparator: these come usually 4 sections in a single package. One can be used as the oscillator to produce the triangular waveform and another to do the comparing, so a complete oscillator and modulator can be done with half an IC and maybe 7 other bits.

The triangle waveform, which has approximately equal rise and fall slopes, is one of the commonest used, but you can use a saw tooth (where the voltage falls quickly and rinses slowly). You could use other waveforms and the exact linearity (how good the rise and fall are) is not too important.

Traditional solenoid driver electronics rely on linear control, which is the application of a constant voltage across a resistance to produce an output current that is directly proportional to the voltage. Feedback can be used to achieve an output that matches exactly the control signal. However, this scheme dissipates a lot of power as heat, and it is therefore very inefficient.

A more efficient technique employs pulse width modulation (PWM) to produce the constant current through the coil. A PWM signal is not constant. Rather, the signal is on for part of its period, and off for the rest. The duty cycle, D, refers to the percentage of the period for which the signal is on. The duty cycle can be anywhere from 0, the signal is always off, to 1, where the signal is constantly on.

PI CONTROLLER

The general block diagram of the PI speed controller is shown in Figure.

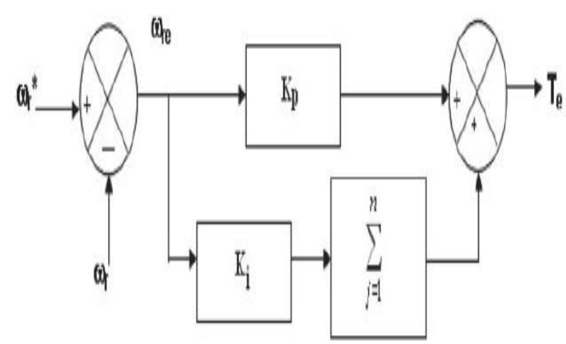


FIG. 2. Block diagram of PI speed controller.

The output of the speed controller (torque command) at n-th instant is expressed as follows:

$Te(n)=Te(n-1)+Kp\_\omega re(n)+Ki\omega re(n)$

Where Te (n) is the torque output of the controller at the n-th instant, and Kp and Ki the proportional and integral gain constants, respectively.

A limit of the torque command is imposed as

$$T_{e(n+1)} = \begin{cases} T_{emax} & \text{for} \quad T_{e(n+1)} \geq T_{emax} \\ -T_{emax} & \text{for} \quad T_{e(n+1)} \leq -T_{emax} \end{cases}$$

The gains of PI controller shown in (10) can be selected by many methods such as trial and error method, Ziegler–Nichols method and evolutionary techniques-based searching. The numerical values of these controller gains depend on the ratings of the motor.

Advantages and disadvantages

- The integral term in a PI controller causes the steady-state error to reduce to zero, which is not the case for proportional-only control in general.
- The lack of derivative action may make the system more steady in the steady state in the case of noisy data. This is because derivative action is more sensitive to higher-frequency terms in the inputs.
- Without derivative action, a PI-controlled system is less responsive to real (non-noise) and relatively fast alterations in state and so the system will be slower to reach setpoint and slower to respond to perturbations than a well-tuned PID system may be.

Integral control:

Like the P-Only controller, the Proportional-Integral (PI) algorithm computes and transmits a controller output (CO) signal every sample time, T, to the final control element (e.g., valve, variable speed pump). The computed CO from the PI algorithm is influenced by the controller tuning parameters and the controller error, e(t).

- PI controllers have two tuning parameters to adjust. While this makes them more challenging to tune than a P-Only controller, they are not as complex as the three parameter PID controller.
- Integral action enables PI controllers to eliminate offset, a major weakness of a P-only controller. Thus, PI controllers provide a balance of complexity and capability that makes them by far the most widely used algorithm in process control applications.

The PI Algorithm While different vendors cast what is essentially the same algorithm in different forms, here we explore what is variously described as the dependent, ideal, continuous, position form:

$$CO = CO_{bias} + Kc \cdot e(t) + \frac{Kc}{Ti} \int e(t)dt$$

Where:

CO = controller output signal

CO_{bias} = controller bias or null value; set by bumpless transfer as explained below

e(t) = current controller error, defined as SP – PV

SP = set point

PV = measured process variable

Kc = controller gain, a tuning parameter

Ti = reset time, a tuning parameter

The first two terms to the right of the equal sign are identical to the P-Only controller referenced at the top of this article.

The integral mode of the controller is the last term of the equation. Its function is to integrate or continually sum the controller error, e(t), over time.

Some things we should know about the reset time tuning parameter, Ti:

- It provides a separate weight to the integral term so the influence of integral action can be independently adjusted
- It is in the denominator so smaller values provide a larger weight to (i.e. increase the influence of) the integral term.
- It has units of time so it is always positive.

Function of the Proportional Term As with the P-Only controller, the proportional term of the PI controller, Kc·e(t), adds or subtracts from CO_{bias} based on the size of controller error e(t) at each time t.

INVERTER CONTROL SCHEME:

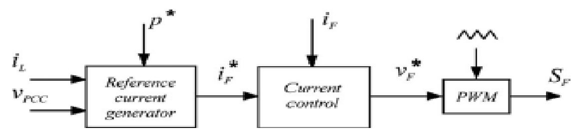


Fig.3. Inverter control scheme

The block diagram of the single-phase inverter control scheme with enhanced power quality features is shown in Fig. 2. The inverter reference current i_F^* is generated by the reference current generator block and the current control is based on a repetitive controller.

A. Reference Current Generator:

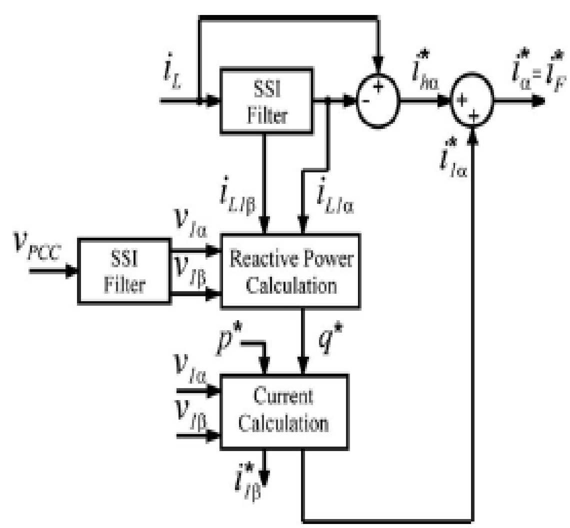


Fig.4. Reference current generation scheme.

The reference current generation scheme is shown in Fig. 3 and can be divided into two parts: the computation of the harmonic current reference $i_{h\alpha}^{*}$ and the generation of the fundamental reference current $i_{f\alpha}^{*}$ corresponding to the active and the reactive power to be generated.

1) Generation of the Harmonic Reference Current:

The nonlinear load current i_L and the PCC voltage v_{PCC} are used to calculate the reference current for current harmonics compensation. A filter based on SSIs (hereinafter called SSI filter) extracts the fundamental frequency component $\omega 0 = 2\times\pi\times 50$ (in radian per second) of the load current in stationary $\alpha\beta$ frame, as shown in Figs. 3 and 4. The harmonic reference current $i_{h\alpha}^{*}$ is obtained from the subtraction of the load current from the output of the SSI filter ($i_L - i_{L1\alpha}$).

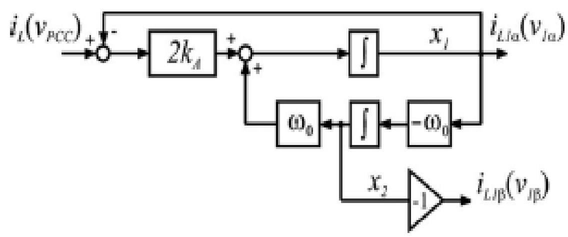


Fig. 5. SSI filter applied for the load current (input is iL and the outputs are $i_{L\alpha}$ and $i_{L\beta}$) and for the PCC voltage (input is vPCC and outputs are $v1\alpha$ and $v_{1\beta}$).

2) Generation of the Fundamental Reference Current:

In steady-state operation, the SSI filter shown in Fig. 4 has two sinusoidal states $x1$ and $x2$ having the same amplitude and being phase-shifted by 90 electrical degree. So, it is possible to obtain two outputs from a SSI filter, $i_{L1\alpha}$ and $i_{L1\beta}$ (which is always 90° shifted respect to $i_{L1\alpha}$). This can be seen by analyzing the two transfer functions of the SSI filter.

$$H_1(s) = \frac{I_{L1\alpha}(s)}{I_L(s)} = \frac{2k_A \times s}{s^2 + 2k_A \times s + \omega_0^2} = \frac{V}{V_P}$$

.... (1)

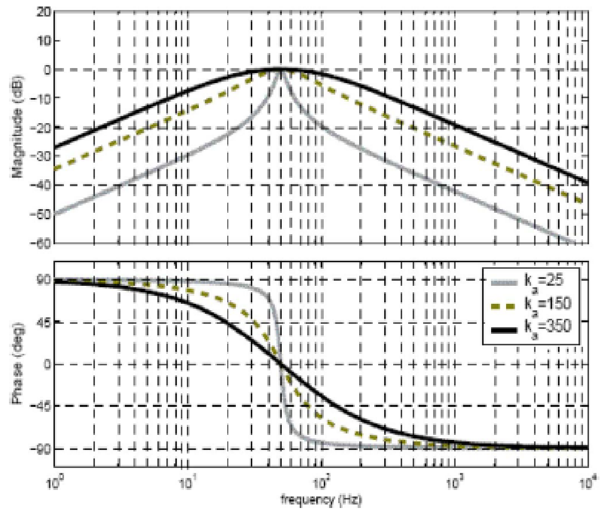
$$H_2(s) = \frac{I_{L1\beta}(s)}{I_L(s)} = \frac{2k_A \times \omega_0}{s^2 + 2k_A \times s + \omega_0^2} = \frac{V}{V_P}$$

.... (2)

In steady-state operation, the relationship between the phases of the transfer functions (1) and (2) in the frequency domain is

$$\angle H_1(j\omega) = \angle H_2(j\omega) + \frac{\pi}{2}.$$

.... (3)



Graph .1 Bode plots of $H1$ (s).

The Bode diagrams of (1) and (2) that are shown in Figs. 5 and 6 for different values of k_a confirm (3). It is also possible to see that when k_A becomes smaller, the filter becomes more selective. However, when this happens, the phase delay becomes higher around the fundamental frequency $\omega 0$.

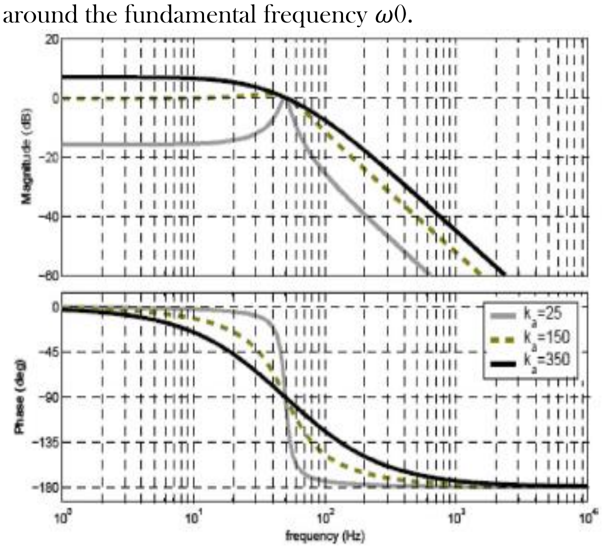


Fig.6. Bode plots of $H2$ (s).

This property is useful for obtaining the orthogonal fundamental components needed to perform the reactive power compensation of the local load. The signal $i_{L1\beta}$ is generated by the SSI only to calculate the fundamental reactive power reference q^{*}, using the definition of reactive power from IRP theory as follows:

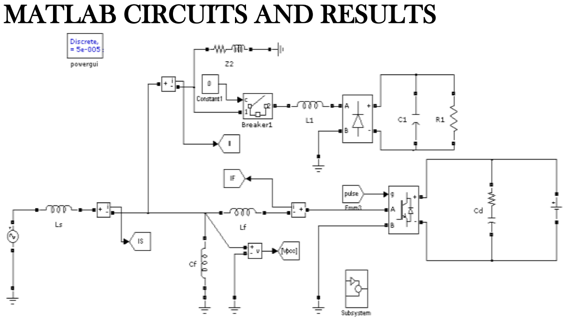
$$q^* = i_{L1\alpha} v_{1\beta} - i_{L1\beta} v_{1\alpha}.$$ .... (4)

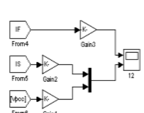
To obtain $v_{1\alpha}$ and $v_{1\beta}$, another SSI filter is used in the PCC voltage vPCC by generating $v1\alpha$ and a signal ($v_{1\beta}$) with the same amplitude and phase-shifted by 90 electrical degrees from $v_{1\alpha}$ as shown in Fig. 4. The use of an SSI filter in the PCC voltage makes the reference current generator insensitive to grid voltage distortions. The fundamental components of the inverter reference current $i_{1\alpha}^*$ and $i_{1\beta}^*$ are calculated by imposing the reference power p^* equal to the amount of active power to be injected into the grid, as follows:

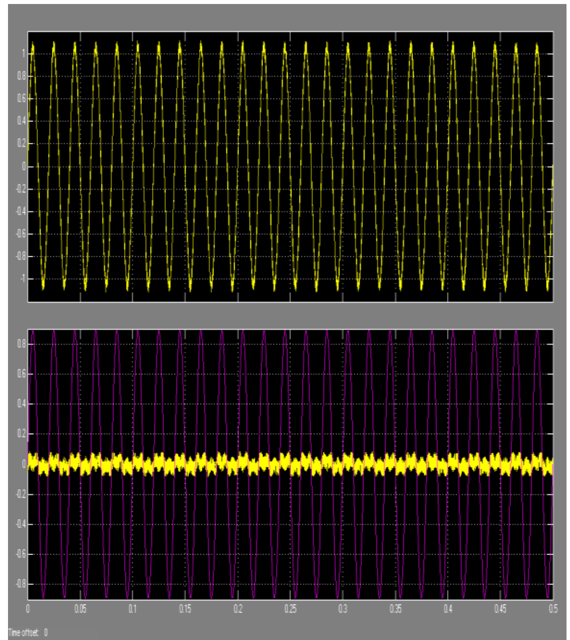
$$\begin{bmatrix} i_{1\alpha}^* \\ i_{1\beta}^* \end{bmatrix} = \frac{1}{v_{1\alpha}^2 + v_{1\beta}^1} \begin{bmatrix} v_{1\alpha} & v_{1\beta} \\ v_{1\beta} & -v_{1\alpha} \end{bmatrix} \times \begin{bmatrix} p^* \\ q^* \end{bmatrix}$$
.... (5)

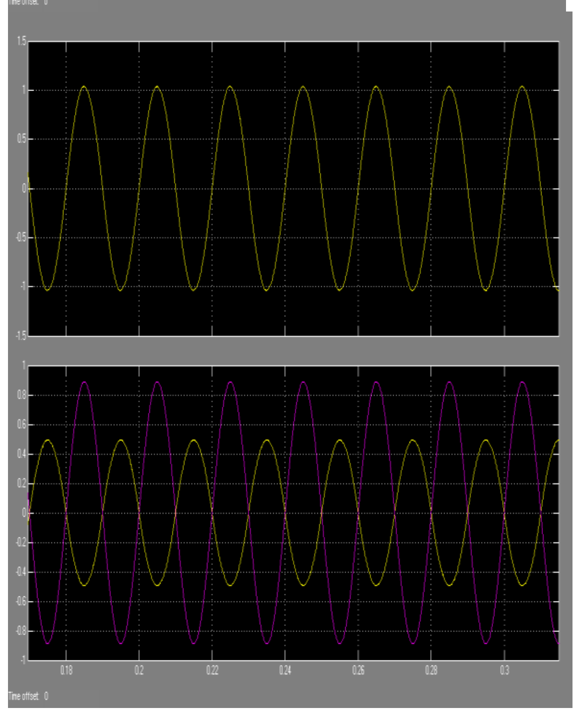
Since the system is single phase, the current $i_{1\beta}^*$ is neglected and $i_{1\alpha}^*$ is added to the harmonic reference current $i_{h\alpha}^*$ to obtain the inverter reference current. The SSI filter used to extract the fundamental component of the nonlinear load current is very flexible, and the gain kA (see Fig. 4) can be adjusted to improve the selectivity of the reference generator or to improve its transient response. It is important to emphasize the difference between the solution used in this paper to create the fictitious variable and another existing method. In the proposed technique, the orthogonal fundamental component signals, used for current reference generation and obtained from the SSI filter, are sinusoidal and phase shifted by 90◦. In the existing method, the obtained fictitious variable is a signal with a high harmonic content generated by phase shifting all frequencies of the load current by 90◦. In this case, some phase delay is introduced in the fictitious variable and implicitly in the inverter current reference.

MATLAB CIRCUITS AND RESULTS









CONCLUSION

This paper deals with a single-phase H-bridge inverter for DG systems, requiring power quality features as harmonic and reactive power compensation for grid-connected operation. The proposed control scheme employs a current reference generator based on SSI and IRP theory, together with a dedicated repetitive current controller. The grid-connected single-phase H-bridge inverter injects active power into the grid and is able to compensate the local load reactive power and also the local load current harmonics.

Experimental results have been obtained on a 4-kVA inverter prototype tested for different operating conditions, including active power generation, load reactive power compensation, and load current harmonic compensation. The experimental results have shown good transient and steady state performance in terms of grid current THD and transient response.

The integration of power quality features has the drawback that the inverter will also deliver the harmonic compensation current with the direct consequence of increase the inverter overall current and cost. A current limitation strategy should be implemented and if the inverter output current exceeds the switch rating, then the supplied harmonic current must be reduced. In this way, the inverter available current is mainly used for active power injection and if there is some current margin, this can be used for the compensation of reactive power and nonlinear load current harmonics. An analysis of the inverter design that takes into account the current required for reactive power and current harmonics compensation is beyond the paper scope and it will be subject of future study. Comparing with conventional topologies the proposed topology reduces conduction losses and improves power quality. The performance evaluation of multiple output SMPS is done under steady state, varying input voltage. The performance of this SMPS is simulated in MATLAB/simulink environment.

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