

Repetitive Control with Adaptive Sampling Frequency for Wind Power Generation Systems

¹P.Dileep Kumar

¹Assistant Professor, Department of Electrical and Electronics Engineering,

¹Brilliant Group of Institutions, Ranga Reddy, Telangana India.

ABSTRACT: - This paper presents a novel repetitive control (RC) for wind power generation system (WPGS), which achieves optimal performance in steady-state conditions due to a variable sampling/switching period technique (VSPT). The main objective of VSPT is to obtain an integer number of samples per grid period. Which solves the main problem of RC, i.e., the loss of rejection to periodic disturbance due to grid frequency is adjusted with a variable sampling period filter phase-locked loop, which also adds robustness to the system due to its inherent tolerance to grid voltage distortion and unbalances, and events such as frequency steps and faults. The control and synchronism subsystems are described, designed, and verified experimentally in a obtained prove the accuracy of the proposed control even under servant disturbances, typically in grids with high WPGS penetration, providing ancillary functions to enhance reliability and reduce operational cost.

I. INTRODUCTION

The world energy scenario is changing abruptly. The huge power demand the world face is becoming a challenge to human day by day. Technology improvements have helped to face this situation better, but it also have created other more challenges regarding the quality of power and efficiency. The conventional energy sources that we relied upon are in stage of being replaced by the renewable energy sources that are widely available. Recent researches focus mainly on the solar energy that almost all the part of this world receives abundantly with variation in its potential. Many studies have made it possible to convert these energies in to more efficient electrical energy. The intervention of power electronics in almost of all the fields have made more sophistication in industries with loads that require the most efficient and accurate amount of supply. The terminology Maximum power point tracking came in to existence with all these conditions. MPPT is a method to obtain the maximum power from a module in any weather condition. As solar energy is varying in nature, the MPPT is the main focus of energy

conservation. By the V-I characteristics of solar energy, there is only one point in its curve where the maximum power is achieved. Tracking that particular point with accuracy has developed many algorithms in this field. Just as the energy that is variable, the techniques used to track the MPP vary under different circumstances. All algorithms will not suit every module in general. Thus choosing an appropriate MPPT technique is also a big deal in this scenario. Wide studies are being made regarding the techniques that are to be chosen for particular circuit or system. In this paper a trial is made to analyze various situations and the techniques used, to give a brief study in that area.

II. CONTROL STRUCTURE AND PRINCIPLES

The WPGS control system can be observed, where the VSPF-PLL output governs the sampling/switching period value, $T_s = 1/f_s$, which feeds the pulse width modulator (PWM). This in turn generates the start-of-conversion signal For the analog-to-digital converters (ADCs). Thus, the whole system operates with a frequency f_s that is an exact multiple of f_g , $f_s = N f_g$. During normal operation, grid frequency drifts are small (e.g., $\leq 2\%$), so f_s keeps close to its nominal value. As a consequence, the variation over time in the spectral content due to f_s is negligible, hence switching losses are approximately the same and the grid filter design can be left unchanged.

A. Current Control

A block diagram of the control structure adopted . Due to the VSPT, the sampling time T_s follows the grid period T_g , which changes slowly. This small and slow drift allows to treat the variable-time discrete system. as a fixed-time one with negligible error [29]. A further discussion and stability analysis due to the variable sampling frequency is performed in Section IV-E. $P(z)$ is the plant transfer function comprised by the modulator, the inverter, the LCL filter, and the

grid. Signal i_g is the current injected into the grid, i_o is the inverter output current, and i_c is the capacitor Current. Notice from Fig. 1 that $i_g = i_o - i_c$, i_d is the reference (desired) current. Since only i_o is measured, i_g will only follow i_d if i_c is effectively compensated by the feed forward term i_{c} , which is added to i_d . The exogenous signal i_p represents the multiple disturbances affecting the output current: grid voltages not completely canceled by feed forward techniques [31], and inverter nonlinearities such as dead times [8], among others. Spectral components of i_p are assumed to be at fundamental and harmonic multiples of the grid frequency. $C(z)$ is a current regulator closing an inner loop to provide fast response to transients, typically within a few milliseconds. Classic control strategies, such as proportional, DBP or SFB controllers are typically employed. From Fig. 2, the resulting inner closed-loop transfer function is

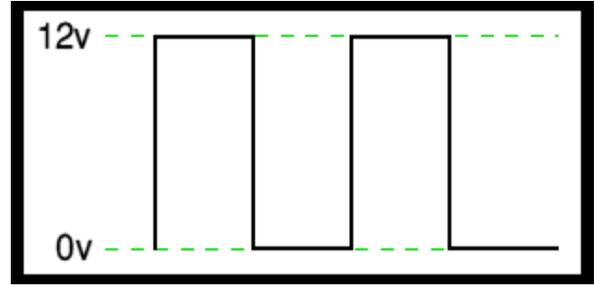
$$H(z) = I_o(z)$$

$$I_d(z) = C(z)P(z) 1 + C(z)P(z)$$

A plug-in repetitive controller $R(z)$ can be attached to $C(z)$ in a cascaded structure, as in Fig. 2, to improve the control loop disturbance rejection. According to the internal model principle [32], $R(z)$ must add poles to the open-loop transfer function at dc ($z = 1$), fundamental, and harmonic frequencies of the grid to ensure that i_p is completely rejected in steady state.

III. PULSE WIDTHS 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.



A. WHY THE PWM FREQUENCY IS IMPORTANT:

The PWM is a large amplitude digital signal that swings from one voltage extreme to the other. And, this wide voltage swing takes a lot of filtering to smooth out. When the PWM frequency is close to the frequency of the waveform that you are generating, then any PWM filter will also smooth out your generated waveform and drastically reduce its amplitude. So, a good rule of thumb is to keep the PWM frequency much higher than the frequency of any waveform you generate.

Finally, filtering pulses is not just about the pulse frequency but about the duty cycle and how much energy is in the pulse. The same filter will do better on a low or high duty cycle pulse compared to a 50% duty cycle pulse. Because the wider pulse has more time to integrate to a stable filter voltage and the smaller pulse has less time to disturb it the inspiration was a request to control the speed of a large positive displacement fuel pump. The pump was sized to allow full power of a boosted engine in excess of 600 Hp.

At idle or highway cruise, this same engine needs far less fuel yet the pump still normally supplies the same amount of fuel. As a result the fuel gets recycled back to the fuel tank, unnecessarily heating the fuel. This PWM controller circuit is intended to run the pump at a low speed setting during low power and allow full pump speed when needed at high engine power levels.

B. PWM CONTROLLER FEATURES:

This controller offers a basic “Hi Speed” and “Low Speed” setting and has the option to use a “Progressive” increase between Low and Hi speed. Low Speed is set with a trim pot inside the controller box. Normally when installing the controller, this speed will be set depending on the minimum speed/load needed for the motor. Normally the controller keeps the motor at this Lo Speed except

when Progressive is used and when Hi Speed is commanded (see below). Low Speed can vary anywhere from 0% PWM to 100%.

Progressive control is commanded by a 0-5 volt input signal. This starts to increase PWM% from the low speed setting as the 0-5 volt signal climbs. This signal can be generated from a throttle position sensor, a Mass Air Flow sensor, a Manifold Absolute Pressure sensor or any other way the user wants to create a 0-5 volt signal. This function could be set to increase fuel pump power as turbo boost starts to climb (MAP sensor). Or, if controlling a water injection pump, Low Speed could be set at zero PWM% and as the TPS signal climbs it could increase PWM%, effectively increasing water flow to the engine as engine load increases.

This controller could even be used as a secondary injector driver (several injectors could be driven in a batch mode, hi impedance only), with Progressive control (0-100%) you could control their output for fuel or water with the 0-5 volt signal.

Progressive control adds enormous flexibility to the use of this controller. Hi Speed is that same as hard wiring the motor to a steady 12 volt DC source. The controller is providing 100% PWM, steady 12 volt DC power. Hi Speed is selected three different ways on this controller:

1) Hi Speed is automatically selected for about one second when power goes on. This gives the motor full torque at the start. If needed this time can be increased (the value of C1 would need to be increased).

2) High Speed can also be selected by applying 12 volts to the High Speed signal wire. This gives Hi Speed regardless of the Progressive signal.

When the Progressive signal gets to approximately 4.5 volts, the circuit achieves 100% PWM – Hi Speed.

C. VOLTAGE SOURCE INVERTER (VSI)

A voltage-source converter is a power electronic device that connected in shunt or parallel to the system. It can generate a sinusoidal voltage with any required magnitude, frequency and phase angle. The VSI used to either completely replace the voltage or to inject the “missing voltage”.

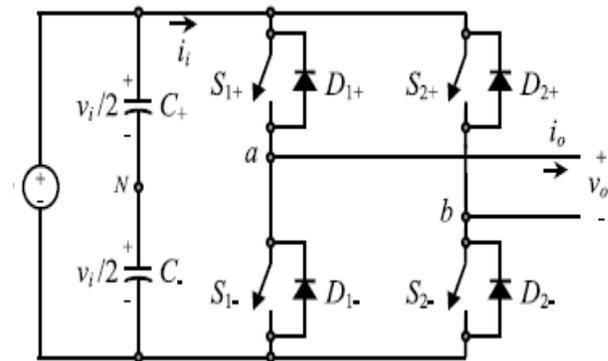
The “missing voltage” is the difference between the nominal voltage and the actual. It also converts the

DC voltage across storage devices into a set of three phase AC output voltages

Full-Bridge VSI:

The power topology of a full-bridge VSI. This inverter is similar to the half-bridge inverter; however, a second leg provides the neutral point to the load. As expected, both switches S1. and S1y (or S2. and S2y) cannot be on simultaneously because a short circuit across the dc link voltage source vi would be produced. There are four defined and one undefined

The undefined condition should be avoided so as to be always capable of defining the ac output voltage. In order to avoid the short circuit across the dc bus and the undefined ac output voltage condition, the modulating technique should ensure that either the top or the bottom switch of each leg is on at any instant. It can be observed that the ac output voltage can take values up to the dc link value vi , which is twice that obtained with half-bridge VSI topologies. Several modulating techniques have been developed that are applicable to full-bridge VSIs. Among them are the PWM (bipolar and unipolar) techniques.



D. CONTROLLING STATAGIES

1. Current Control

A block diagram of the control structure adopted is shown in Fig.. Due to the VSPT, the sampling time Ts follows the grid period Tg, which changes slowly. This small and slow drift allows to treat the variable-time discrete system as a fixed-time one with negligible error [29]. A further discussion and stability analysis due to the variable sampling frequency is performed in Section IV-E. P(z) is the plant transfer function comprised by the modulator, the inverter, the LCL filter, and the grid. Signal ig is the current injected into the grid, io is the inverter

output Current, and i_c is the capacitor current. Notice from Fig. 1 that $i_g = i_o - i_c$. In Fig. 2, i_d is the reference (desired) current. Since only i_o is measured, i_g will only follow i_d if i_c is effectively compensated by the feedforward term i_{c} , which is added to i_d . The exogenous signal i_p represents the multiple disturbances affecting the output current: grid voltages not completely canceled by feedforward techniques [31], and inverter nonlinearities such as dead times [8], among others. Spectral components of i_p are assumed to be at fundamental and harmonic multiples of the grid frequency. $C(z)$ is a current regulator closing an inner loop to provide fast response to transients, typically within a few milliseconds. Classic control strategies, such as proportional, DBP or SFB controllers are typically employed. the resulting inner closed-loop transfer function is

$$H(z) = I_o(z) Id(z) / C(z)P(z) 1 + C(z)P(z)$$

2. Comparison With Other RC Approaches

An important drawback of RC is its gain loss when the grid frequency varies, which, in turn, reduces the control Loop disturbance rejection and reference tracking capability [20]. This occurs because the order N of the RC is not equal to the ratio T_g/T_s , and hence the RC poles no longer lie at multiples of fg . Several approaches have been proposed in the literature to deal with this issue, the most common being the introduction of a fictitious sampler operator [26]. A recent and more sophisticated approach uses an FIR filter with variable coefficients within the RC algorithm to emulate the fractional delay produced by the frequency drift [27]. A similar approach is found in [28], which employs a simple first-order low-pass filter, cascaded with the RC delay line, with adjustable cutout Frequency. This is much simpler than the FIR filter in [27], hence the computational cost is reduced at the expense of a degraded performance. In both cases, the filter coefficients must be accurately updated online to avoid Additional loss of performance; the proposed RC does not require any parameter update. In addition, both [27] and [28] suffer from coefficient quantization errors. In the proposed strategy, the VSPT allows the use of the simple RC algorithm (3) consisting of a delay and simple filters in $Q(z)$ and $L(z)$ (which are presented in detail in Section IV), where the aforementioned numerical errors are nonexistent since all the coefficients are one or powers of two.

The gain of several RC algorithms, operating with fixed $T_s = 100\mu s$ and for a grid

frequency of 49.38 Hz, a 1% variation from the nominal value of 50 Hz. The static RC, described by (2) and using a fixed order $N = 200$, exhibits the worst performance under grid frequency changes. The adaptive RC reduces the gain loss by setting online the order N to the nearest integer of the estimated signal period. The adaptive RC with linear interpolation further reduces the gain loss, for which a precise estimation of the grid frequency is required to update the algorithm coefficients. In all the cases described, notice the significant reduction in the RC gain, which may lead to high Distortion in the output currents. For high-order harmonics, the RC could even amplify disturbances (negative gain in decibels), which is the case for the static

3. Variable Sampling Period Filter Phase-Locked Loop

The three-phase VSPF-PLL [30] operates with a variable sampling period technique. As shown in Fig. 1, the PLL receives the sampled three-phase voltages, which are transformed to the SRF, and the q component is used as an estimate of the phase error. A sliding-window filter (SWF) is applied to reject signals different from the fundamental positive sequence. This feature provides robustness to the VSPF-PLL against grid voltage distortions, unbalances, and faults. After the SWF, a lead-lag compensator with integral action is used to obtain a stable closed loop with zero steady state error. The output of this compensator is the value of T_s , which is updated in the PWM for the next period. A reference phase, ϕ_u , is internally generated by adding a phase step equal to $2\pi/N$ on each new sampling period. ϕ_u is employed to transform the sampled voltage to the SRF, so the loop will increase or reduce T_s to match ϕ_u to the actual positive sequence phase. ϕ_u is also sent to the control block to generate the current reference signals. The VSPF-PLL mathematical model, together with the design of the lead-lag compensator and the SWF, is escribed in detail in [30]. The VSPF-PLL distinctive component is the SWF, whose transfer function is

$$GSWF(z) = \frac{1 - z^{-NSWF}}{1 - z^{-1}} \quad (8)$$

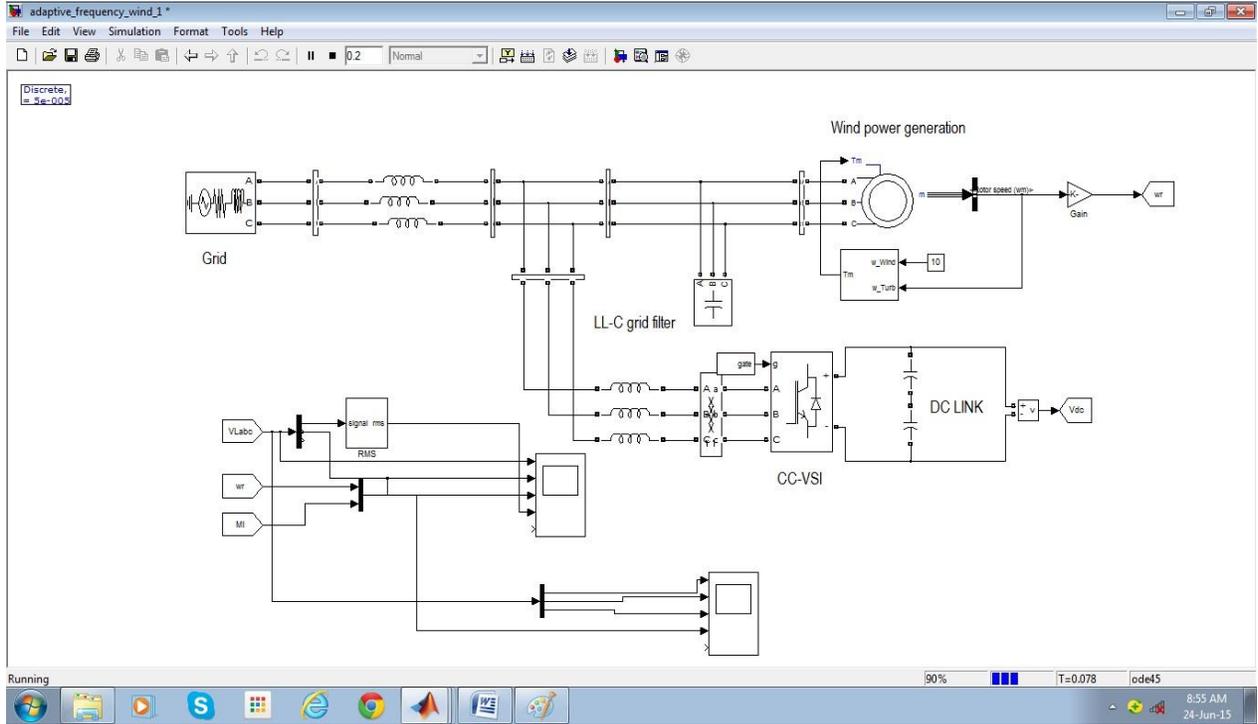
This shares some properties with the RC, clearly visible by comparing it with (2). While (2) places N poles equally spaced along the unitary circle, (8) places $NSWF$ zeros in the same places. Parameter $NSWF$ is chosen as N or $N/2$

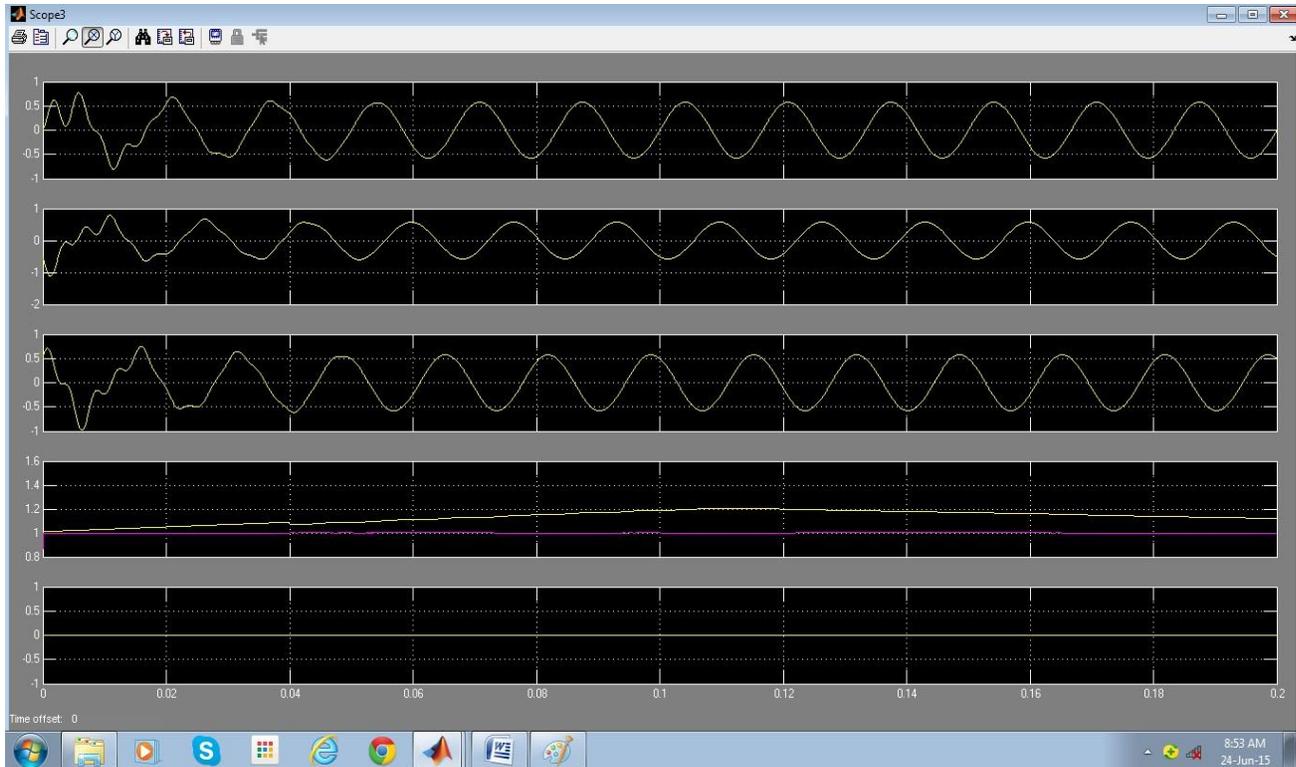
Whether even harmonic components are significant or not in the grid voltages. If they are not, $NSWF = N/2$ can be used, reducing memory positions by half. Notice that the zero in $z = 1$ is

canceled by a pole in such place, allowing to pass only the dc component of the estimated phase error

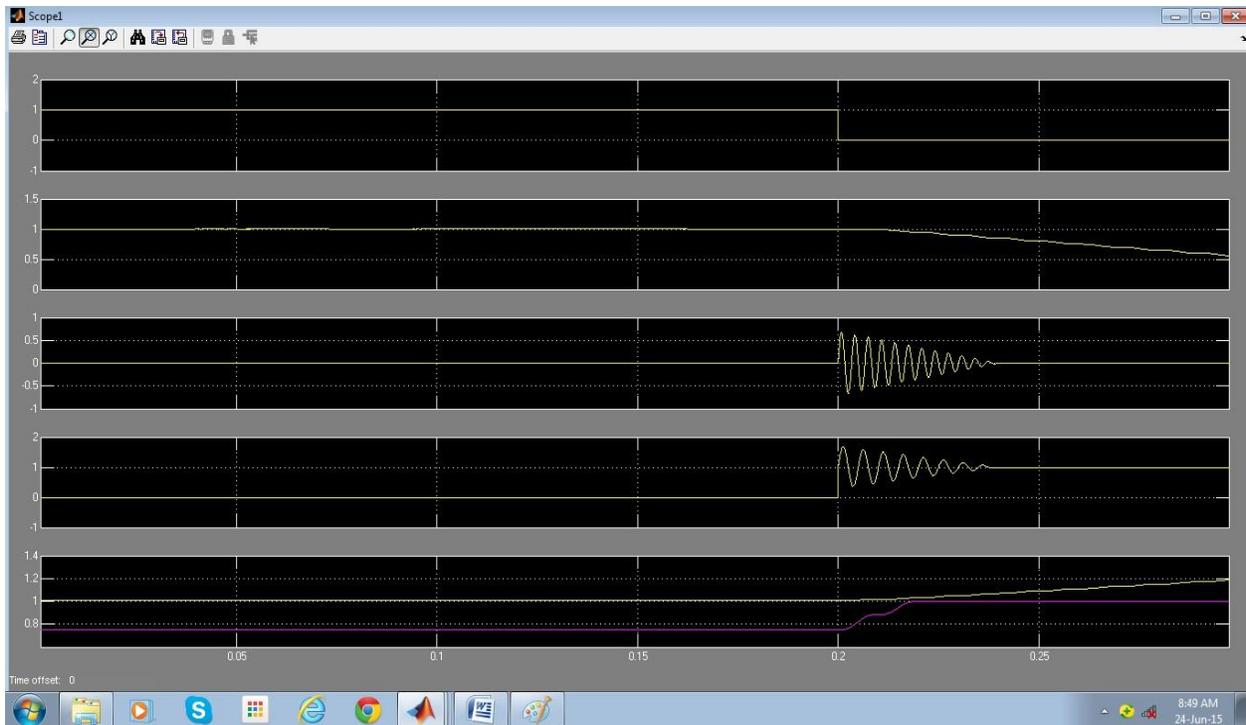
IV. MAT LAB AND SIMULATION

Without fault





WITH FAULT:



Comparative results of the transient response employing the proposed control combined with both

a standard SRF-PLL and the VSPF-PLL under severe grid disturbances and faults. (a) Grid voltages. (b) Currents with SRF-PLL. (c) Currents with VSPF-PLL. (d) SRF-PLL output. (e) VSPF-PLL output

V. CONCLUSION

An RC for WPGS was presented, which achieves optimal performance in steady-state Conditions due to a VSPT. With this new control strategy, the loss of rejection due to grid frequency drift is corrected, as proven by the Experimental results. The sampling/switching frequency is slightly adjusted around 10 kHz with a VSPF-PLL, which also adds robustness to the system due to its inherent tolerance to grid voltage distortion and unbalances, and events like frequency steps and grid faults. Since grid frequency drift is usually small during inverter operation, switching losses and LCL filter design remained unaffected by the variable frequency. Experimental results with a 10-kW WPGS also showed that distortion of injected currents remained very low ($THDi < 1\%$) even under severe inverter nonlinearities (dead times of $2.5 \mu\text{s}$), grid voltages with high harmonic content ($THDv \approx 5\%$), grid frequency variations of $\pm 5\%$, and sudden grid faults. Convergence times were within a few grid cycles: three cycles to achieve $THDi < 5\%$, and less than 10 cycles to achieve $THDi < 1\%$ (steady-state value). This ensures a good tracking of the WPGS active and reactive power flow requirements, e.g., to maximize wind power extraction from gusts in small urban wind turbines and to help the grid to stabilize voltage fluctuations. Computational times in a state-of-the-art DSP were about 15% of a control period of $100 \mu\text{s}$, which includes RC and PLL algorithms, proving that the solution is computationally efficient. The implementation of the variable frequency sampling is straightforward as it only requires a few standard hardware modules (configurable ADCs and PWMs), which are already embedded in the selected DSP. The proposed RC was compared through the experimental tests to other control strategies: an RPCC and a PR + HC. The tests showed the superiority of the method: $THDi = 6.6\%$ and computational cost of $11 \mu\text{s}$ for the RPCC, $THDi = 4.5\%$ and $18 \mu\text{s}$ for the PR + HC, and finally $THDi = 0.8\%$ and $15 \mu\text{s}$ for the RC.

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