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Tracking error minimization in multi-loop control of UPS inverters using the reference frame transformation

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***Abstract*—The main problem in most existing control methods for uninterruptible power supply (UPS) inverters is their excessive complexity. This problem is successfully solved in multi-loop control methods by simple proportional controllers. Nevertheless, using the simple proportional controllers instead of conventional controllers, such as a proportional-resonant (PR) or a proportional-integral (PI) controller, leads to several disadvantages such as the steady state and transient errors. This paper investigates the multi-loop control scheme by proportional controllers using a reference frame transformation for single-phase UPS inverters. The proposed control method uses two nested proportional controllers in the synchronous reference frame. In fact, the steady state error of the UPS inverter in response to the ramp function changes to the steady state error in response to the step function using the reference frame transformation. Excellent tracking performance, no need to any derivative or integrator, fast dynamic response and simplicity of design and implementation are some advantages of the proposed method. The feasibility of the proposed control method is confirmed through simulations in MATLAB/SIMULINK.**

Keywords—Reference frame transformation; Tracking error; Multi-loop control; Single-phase UPS inverter.

I. INTRODUCTION

Recent developments in distributed generation (DG) show the high potential of these resources as a good replacement for conventional power supply systems, especially for electrification of remote areas or sensitive loads. Generally, an interface is required for distributed generation sources to convert generated electricity into AC power with desired voltage and frequency. For this purpose, off-grid power electronic converters, which are called UPS inverters, are used to adjust the output energy of DGs. The UPS inverters act as a controlled voltage source, unlike the grid connected inverters [1-2].

Many control schemes are provided for control of UPS inverters [3-4]. The repetitive controllers, which are based on the internal model principle, in particular, are used in dealing with periodic signals. However, slow dynamics, need for large memory space and poor performance in the presence of non-periodic signals are some disadvantages of this method [5-7].

Also, the non-linear controllers have some good features such as fast dynamics, but these techniques have some drawbacks such as complexity, sensitivity to parameter variations and steady-state errors [8-10].

Various methods have been proposed for multi-loop controllers [11-13], which typically use a combination of load voltage, load current and capacitive or inductive current of LC filter sensors. Major disadvantages associated with multi-loop control schemes are the complexity of the internal and external loops parameters design and need many sensors for measuring of feedback variables. Therefore, in [14 and 15], the complexity of the multi-loop control method was reduced without using proportional-integral (PI) and proportional-resonant (PR) controllers. However, an undeniable tracking error was observed in steady state conditions in [14] and in transient mode in [15].

This paper investigates a new multi-loop control scheme by simple proportional controllers using a reference frame transformation for single-phase UPS inverters. In this method, each of the feedback variables, after creating a virtual phase and transform it from the stationary reference frame to the synchronous reference frame, individually is controlled. Also, to increase reliability and reduce the cost and size, the Kalman filter algorithm is used to estimate the output voltage. Finally, the performance of the proposed control method and comparison with other methods is done by simulating in MATLAB / SIMULINK.

II. SYSTEM MODELING

Block diagram of the power stage of the single-phase UPS inverter with output LC filter is shown in Fig. 1.

Desired values of the circuit parameters are shown in Table 1. According to Fig. 1, the equations, describing the dynamics of UPS inverter, can be extracted.

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TABLE I. SYSTEM PARAMETERS

Symbol	Parameter	Value
f_s	Switching frequency	20 kHz
f	Fundamental frequency	50 Hz
V_{dc}	DC link voltage	150 V
C	Filter capacitance	25 µF
L	Filter inductance	3.7 mH
r_L	Filter resistance	0.2 Ω

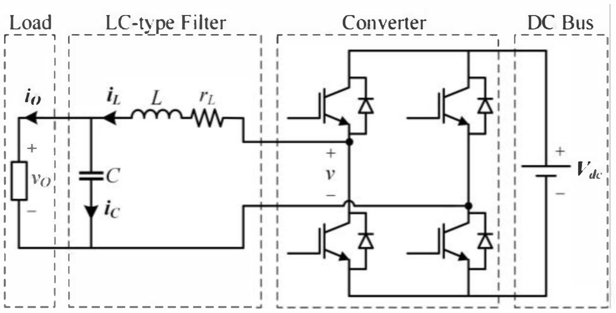

Fig. 1. Power stage of UPS inverter

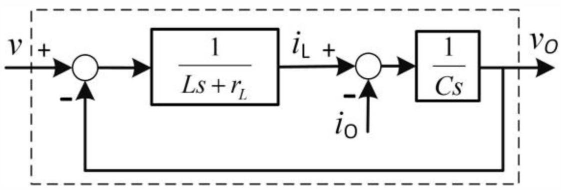

Fig. 2. Block diagram of UPS inverter

$$v = r_L i_L + L\frac{di_L}{dt} + v_O \tag{1}$$

$$i_L = i_O + C\frac{dv_O}{dt} \tag{2}$$

which v, v_O, i_L and i_O are the output voltage of the inverter, the load voltage, the inverter current and load current, respectively. The above equations can be rewritten as the state-space model as:

$$\begin{bmatrix} \dot{i}_L \\ \dot{v}_O \end{bmatrix} = A\begin{bmatrix} i_L \\ v_O \end{bmatrix} + B\begin{bmatrix} v \\ i_O \end{bmatrix}$$
$$A = \begin{bmatrix} -\frac{r_L}{L} & -\frac{1}{L} \\ \frac{1}{C} & 0 \end{bmatrix}, B = \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & -\frac{1}{C} \end{bmatrix} \tag{3}$$

Also, according to (1) and (2), the model of UPS inverter is obtained as shown in Fig. 1.

III. CONTROL OF UPS INVERTER

A. Proposed control structure

Generally, the multi-loop control method of the UPS inverter contains the internal and external feedback loops that used to control current and voltage, respectively. In this method, the outer loop follows the voltage reference signal, while the inner loop guarantees stability in a wide range, fast dynamic and also eliminates the possibility of resonance in output LC filter.

In fact, the multi-loop control method of the UPS inverters use the different combinations of the filter inductor current, filter capacitor current or output current as a control variable in the inner loop [16-20]. As shown in the literature, choosing a filter capacitor current as a variable of the inner loop is more common, because it has greater ability to reject disturbances and due to the low rate compared to other currents, it will be measured with lower price.

Fig. 3 shows the proposed control scheme. This plan includes an outer feedback loop by using a simple proportional controller (K_v) to adjust the output voltage, the internal combined loop by using a simple proportional controller (K_i) to regulate filter capacitor current and a feed forward path of reference voltage to increase system robust performance.

By using this scheme and replacing traditional PR or PI controllers with simple proportional controllers, system analysis and controller design will be substantially simplified, and also the phase delay in the fundamental frequency due to PI or PR controllers will be prevented [21- 25]. As shown in Fig. 3, each of the feedback variables in the proposed control scheme, after creating a virtual phase for them and convert them from stationary reference frame to synchronous reference frame, is controlled individually in two d and q axes. This control scheme has been proposed to minimize the steady state error without using the integrator or derivative. In the following, the inner and outer loops parameters for proposed control scheme are designed in the simple state without creating a virtual phase and using reference frame, and then are used in the final design.

B. Design of the proposed control scheme

- Inner control loop:

In this paper, the proportional coefficients are chosen in accordance with the required bandwidth for control loops. The block diagram of the UPS inverter with the internal control loop and reference voltage feed forward is shown in Fig. 4. The closed-loop transfer function of the considered model is obtained as follows:

$$G_i(s) = \frac{ZCK_i K_{PWM} s}{ZCLs^2 + (ZC(r_L + K_i K_{PWM}) + L)s + Z - ZK_{PWM} + r_L} \tag{4}$$

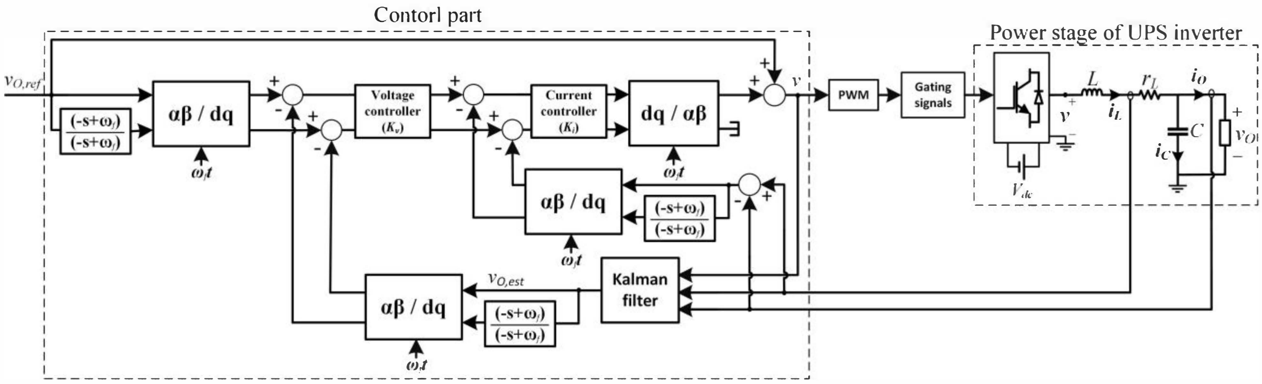

Fig. 3. Proposed control scheme for UPS inverter

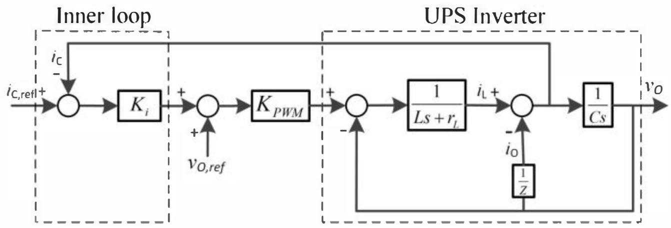

Fig. 4. Block diagram of UPS inverter with internal current loop

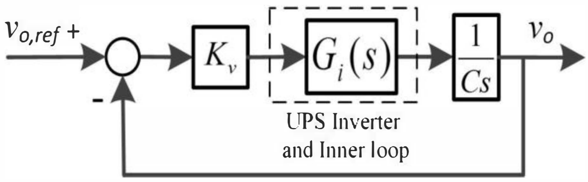

Fig. 5. Simplified block diagram of the proposed control system

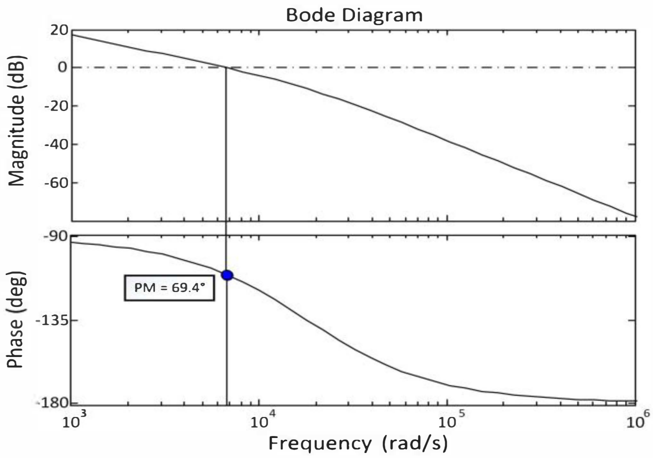

Fig. 6. Open-loop bode plot of the system

which Z, K_i, K_{PWM}, are the load impedance, the proportional controller gain and the PWM modulator gain, respectively.

It should be noted that the inner loop parameter is calculated according to nominal load, because in this case, the lowest bandwidth in comparison with different loads is obtained. Also, the inner loop bandwidth should be low enough than the switching frequency to be safe from switching disturbances. Therefore, the bandwidth is considered one tenth of the switching frequency ($\omega_{bi} = 2\pi(0.1\times f_s) \approx 12.5\,krad/s$). The proportional controller gain is obtained about 66.

- Outer control loop

In the next step, the proportional controller of the outer control loop must be adjusted. The selection of the outer control loop gain (K_v) is a compromise between the bandwidth and controller stability. Fig. 5 shows a simplified block diagram of the proposed control system, in which the UPS inverter model with the inner loop is replaced by $G_i(s)$ from (4).

It should be noted that the phase margin (PM) will be slightly changed, depending on the load conditions. Therefore, the closed-loop system transfer function in Fig.5, with assuming no load condition, is shown as follows:

$$G(s) = \frac{v_o}{v_{o,ref}} = \frac{K_v K_i}{LCs^2 + C(r_L + K_i)s + K_v K_i} \tag{5}$$

The optimal bandwidth of the outer control loop should be more than the nominal frequency of the system and less than the switching frequency, and also less than the bandwidth of the inner loop so dynamic of the inner loop can be ignored in outer loop design. In this paper, the bandwidth of the outer loop is selected between 20 times the fundamental frequency (1000 Hz) and one-tenth the switching frequency (2 kHz), to achieve a fast transient response and switching noise elimination. For this purpose, the voltage control loop bandwidth is considered as 1.5 kHz (ω_{bv} = 2π × 1.5 kHz ≈ 9.42 krad/s).

Calculating (5) similar to the inner loop calculation, the outer loop controller gain is obtained about 0.18. To investigate the stability region, open-loop bode plot of the system is shown in Fig. 6 that the PM is equal to 69.4°. This value for the PM is very suitable for applications in power electronics.

C. Steady-state error of the proposed control scheme

As it is known, the open loop transfer function is obtained as follows (at no load condition):

$$G_{OL}(s) = \frac{K_v K_i}{s(LCs + c(r_L + K_i))} \tag{6}$$

The desired system is a one type system and the steady state error in response to the ramp function and the step function will be calculated as follows, respectively:

$$K_p = \lim_{s \to 0} G_{OL}(s) = \infty \Rightarrow e_{ss} = \frac{1}{1+\infty} = 0 \tag{7}$$

$$K_v = \lim_{s \to 0} sG_{OL}(s) \approx \frac{K_v}{c} \Rightarrow e_{ss} = \frac{c}{K_v} \tag{8}$$

Due to the sinusoidal input, there is a non-negligible error in the system in steady state (equation 8), which is directly related to the amount of capacitance and inversely related to the outer control loop gain. However, reduction in the capacitor value has a positive effect on the estimator accuracy and increasing the outer control loop gain is important for total stability of the system. In this paper, by using a reference frame transformation, the sinusoidal input signal turns into the step signal, and steady-state error is reduced to zero (equation 7).

D. Output voltage estimation with Kalman filter algorithm

The Kalman filter algorithm is a set of equations that estimates the states of a system by minimizing the mean squared errors [26]. The algorithm is composed of two equation categories. The time update equations that predict the states and the error covariance matrix with an early sample to obtain an initial estimation for the next time step, and the measurement update equations that corrects the initial estimates using the measured values, which leads to a final estimate of states and the error covariance matrix in each iteration [27].

In general, linear differential equations of a system with state vector *x*, Input vector *u* and the measurement vector *z* are expressed as follows:

$$\begin{aligned} x_{k+1} &= Ax_k + Bu_k + w_k \\ z_k &= Hx_k + v_k \end{aligned} \tag{9}$$

The random variables w_k and v_k show the process noise and measurement noise, respectively.

For the system described in (9), Fig. 7 depicts a complete picture of the algorithm performance. K_k is Kalman filter coefficient, and P^-_k, P_k, Q and R shows the covariances of initial estimation error, the final estimation error, the process noise and measured noise, respectively.

At each step, in addition to the input signals, the estimated states, previous error covariance and measurement vector is required. It should also be noted that initial values for state and error covariance is required in the initial step, which normally are considered zero.

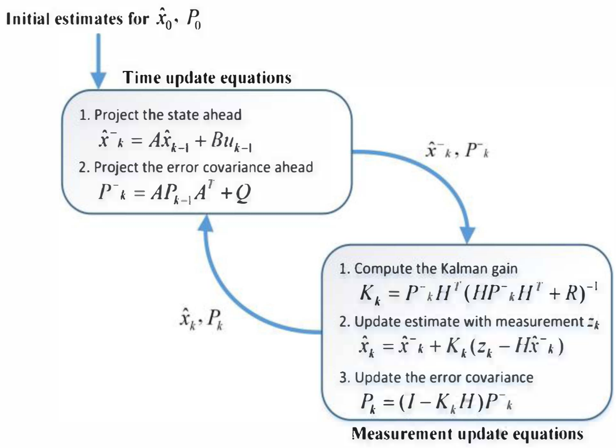

Fig. 7. Kalman filter algorithm performance

In this paper, a Kalman filter algorithm is used to estimate the output voltage. For this purpose, a time-discrete state-space model of the system is needed. The time-discrete model can be obtained from equation (3) with assuming T_s as a sampling time.

$$\begin{bmatrix} i_L(k+1) \\ v_O(k+1) \end{bmatrix} = A_d \begin{bmatrix} i_L(k) \\ v_O(k) \end{bmatrix} + B_d \begin{bmatrix} v(k) \\ i_O(k) \end{bmatrix}$$
$$A_d = \begin{bmatrix} 1 - \frac{r_L T_s}{L} & -\frac{T_s}{L} \\ \frac{T_s}{C} & 1 \end{bmatrix}, B_d = \begin{bmatrix} \frac{T_s}{L} & 0 \\ 0 & -\frac{T_s}{C} \end{bmatrix} \tag{10}$$

By considering the equation (10) for estimation algorithm and measuring the filter inductor current, an estimate of both variables is achieved. Thus, $z(k)=i_L(k)$ and matrices *R* and *Q* are assumed as follows.

$$\begin{aligned} Q &= [1,0;0,1] \\ R &= 1 \end{aligned} \tag{11}$$

It should be noted that the input vector is also composed of the inverter output voltage and the load current, which inverter output voltage is applied by the controller and it's not needed to measure and load current is directly measured by the sensor.

IV. SIMULATION RESULTS

To confirm the performance of the proposed control algorithm, the single-phase converter is implemented by using the MATLAB/SIMULINK software. Simulations have been investigated under linear and non-linear loads in transient and steady states.

Fig. 8 shows the measured output voltage and current, and errors of estimation and control of a linear nominal load. In this case, the output voltage is an appropriate sinusoidal signal

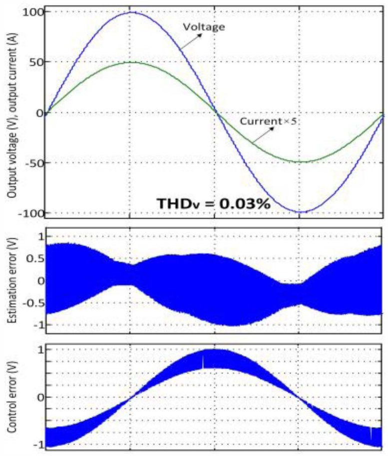

Fig. 8. Measured output voltage, current and errors under the nominal linear load

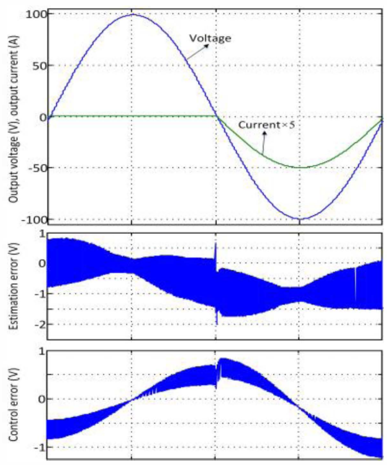

Fig. 9. Measured output voltage, current and errors transient from no load to full load

with the total harmonic distortion (THD) of 0.03%. The estimation error is less than one percent that shows the great accuracy of estimation. Also, the tracking error with using proportional controllers is achieved about one percent that is similar to the steady-state error of PI or PR controllers.

Also, Fig. 9 shows the transient performance against a sudden change from no load to full load. In this case, the transient state quickly disappears and errors of estimation and control almost remain unchanged. In fact, superior transient performance is due to the proper selection of the variable in the inner loop.

The proposed controller is also investigated under a non-linear load, which is shown in Fig. 10. The non-linear load is a diode bridge rectifier coupled with a series resistive-inductive circuit or parallel resistive-capacitive circuit. In this paper, a non-linear load with a THD of about 60% is considered. In this case, despite the large ripples in the current waveform, voltage waveform will remain sinusoidal (THD = 0.86%).

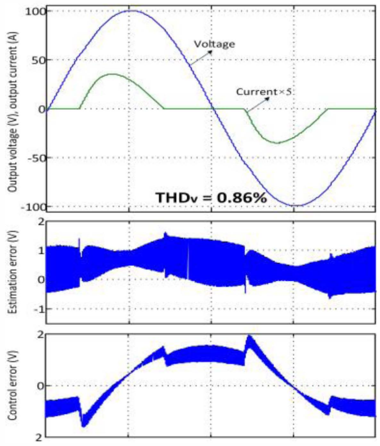

Fig. 10. Measured output voltage, current and errors under a highly non-linear load

V. Conclusion

This paper investigates a multi-loop sensorless control scheme, including simple proportional controllers using a reference frame transformation for the single-phase UPS inverters. The proposed control method uses two nested proportional controllers in the synchronous reference frame. Using the reference frame transformation, the steady state error of UPS inverters in response to ramp function changes to the steady state error in response to the step function. Excellent tracking, no need to any derivative or integrator, fast dynamic, simplicity of design and implementation are some advantages of this method. The performance of the proposed control method is confirmed by the simulation results in MATLAB/SIMULINK.

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