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Multiple feedback-control-loops for single-phase full-bridge PWM inverter

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This paper presents a multiple feedback-loop-control technique for a single-phase full-bridge PWM inverter with output LC filter. The main challenge for an Uninterruptible Power Supply (UPS) is to maintain a high quality sinusoidal voltage under non-linear load conditions as most of the electronic loads are non-linear in nature and for that it needs to be controlled. Multiple feedback consists of two control-loops; one for capacitor voltage and other for inductor current-control. Output voltage and load curren-feedforward-control is used. This technique reduces the distortion in the inverter output voltage and brings it closer to a sine wave. The control concept has been verified using Matlab/ Simulink™ toolbox and the simulation results are obtained with different types of loads.

Keywords: *UPS, analog control, feed forward control*

1.0 INTRODUCTION

Uninterruptible power supplies are widely used for the continuity and quality in the supply of electric power to sensitive loads, like computer systems, medical equipments, telecommunication systems, in power line problems [1]. The main aim of the UPS system is to provide a high quality sinusoidal output voltage with low total harmonic distortion. A clean sinusoidal output voltage is achieved by using a Sinusoidal Pulse Width Modulation (SPWM) technique and LC filter at the output side of the inverter. But, with non-linear load, the PWM scheme does not guarantee low distortion in the load voltage. There is significant increase in the utility voltage distortions because of the growing use of non-linear loads by industrial, commercial and residential consumers. To mitigate the effects caused by non-linear loads on the utility system, feedback controllers are used.

There are many control topologies for the single phase UPS inverters. At present, many feedback control techniques are available to control the inverter output voltage [2]-[6]. This paper presents a voltage and current-control scheme for the inverter stage of the UPS. Two control-loops are included in this controller, an inner inductor current-control-loop and an outer capacitor voltage-control-loop.

2.0 OPEN LOOP INVERTER

The basic topology of the single-phase full-bridge PWM inverter with LC filter and load is shown in Figure 1. The system variables and parameters are defined in Table 1.

Unipolar SPWM scheme is used to create proper gating signals for the inverter switches as this method effectively doubles the switching frequency of the inverter voltage, making the output LC filter smaller and cheaper. The output voltage of the bridge can be $+V_{DC}$, $-V_{DC}$ or zero depending on how the switches are controlled.

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The output voltage is switched either from $+V_{DC}$ to zero or form $-V_{DC}$ to zero.

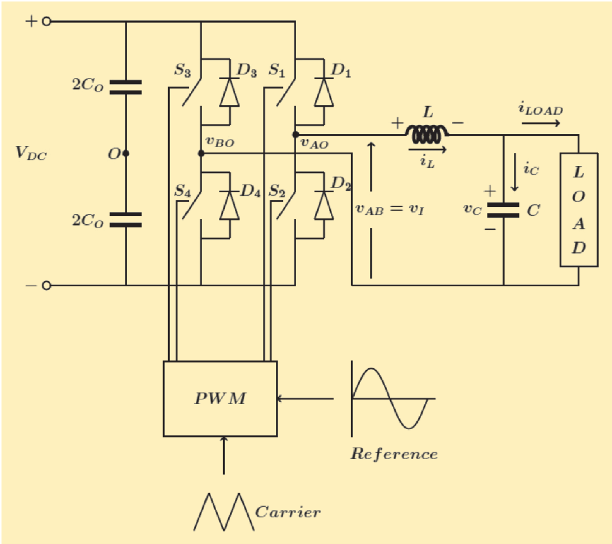

FIG. 1 BLOCK DIAGRAM OF FULL BRIDGE INVERTER

TABLE 1	
DEFINITION OF SYSTEM VARIABLES AND PARAMETERS	
Var.	Definition
V_{DC}	DC Bus voltage
C_O	DC link capacitor
i_L	Current through filter inductor
i_L*	Reference inductor current
v_c	Voltage across filter capacitor
v_c*	Reference capacitor voltage
i_c	Current through filter capacitor
i_c*	Reference capacitor current
i_{LOAD}	Load current
m*	Reference signal to PWM modulator
v_I	Full-bridge output voltage
K_{inv}	Inverter gain

Figure 2 shows the inverter output voltage and current waveform in case of non-linear load i.e. diode rectifier with capacitor filter with 80 % modulation index. We can see that the load current of the inverter deviates significantly from the sinusoidal nature. This distorted current leads to distortion in the inverter output voltage which is not desirable at all. It is necessary to get the desirable sinusoidal voltage with low THD for any kind of load. So, we are using feedback controller to regulate the output voltage of the inverter.

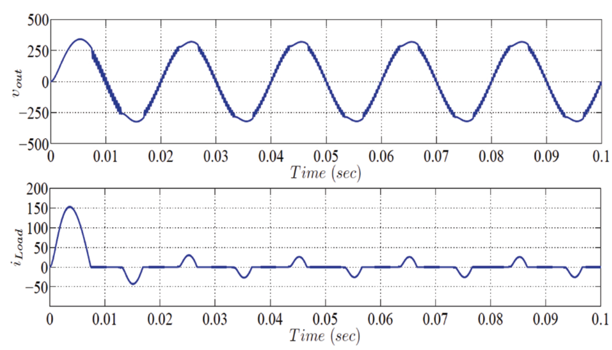

FIG. 2 INVERTER OUTPUT VOLTAGE AND LOAD CURRENT FOR 1500 W NON-LINEAR LOAD

3.0 VOLTAGE AND CURRENT CONTROLLER

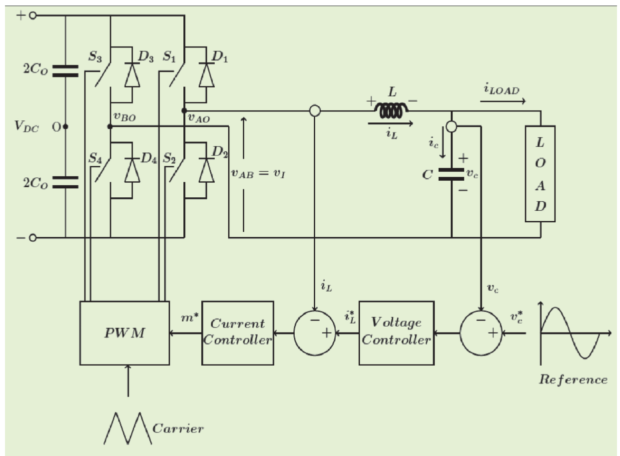

FIG. 3 BLOCK DIAGRAM OF PWM INVERTER WITH FEEDBACK CONTROLLER

Figure 3 shows the block diagram of the inverter with controller. The controller used here is a PI controller. The function of the voltage-control-loop is to set the output voltage to the output voltage reference value. The actual output voltage is compared with the reference output voltage and the error signal is given to the PI voltage controller. The controller processes this error. If the actual output voltage is less than the reference voltage, it will increase the current limit reference as the voltage controller output is used as inductor current reference [7-11].

The current controller minimizes the error between the measured inductor current and the reference current. The output of the current controller is the reference signal to the PWM modulator required for the generation of gating signals to the inverter switches. If the feedback current is less than the reference current, the controller increases the reference signal i.e. duty of the switches till it meets the required current value. For a given voltage control, the inner current-control-loop will execute till $i_L = i_L^*$. So the inner control-loop should be faster than the outer control-loop.

The complete plant and controller modeling block diagram of the inverter is shown in Figure 4. Here, the inverter gain is assumed as unity so that $m^* = v_I$.

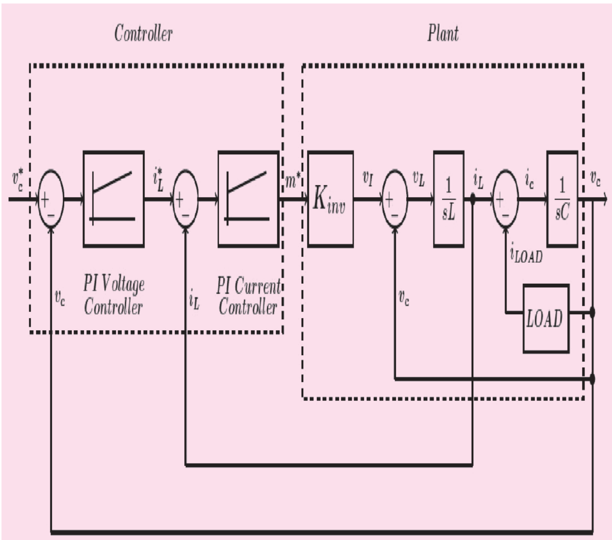

FIG. 4 MODELING DIAGRAM OF INVERTER WITH CONTROLLER

4.0 DESIGN OF CURRENT-LOOP

Let us consider only current-loop of the inverter. The current controller controls i_L by controlling v_L. Here, v_c acts as disturbance. The current controller has to unnecessarily generate v_c. The output voltage disturbance v_c is compensated through output voltage feed forward as shown in Figure 5 so that the controller needs to generate only v_L^*. Figure 6 gives the simplified current-loop which shows that the current-loop is independent of the output voltage disturbance.

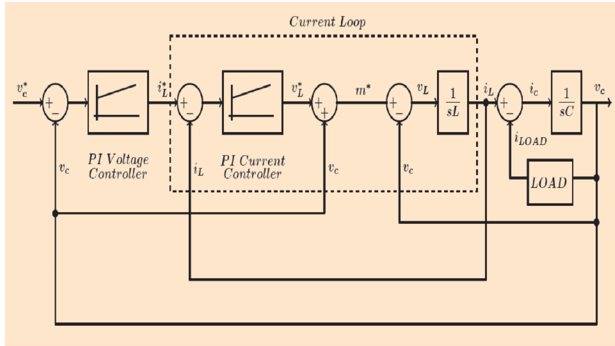

FIG. 5 OUTPUT VOLTAGE FEEDFORWARD CONTROL

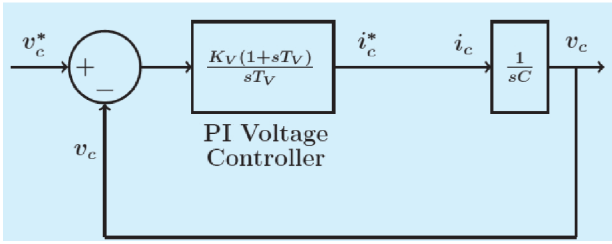

FIG. 6 SIMPLIFIED CURRENT-LOOP

The closed loop transfer function of the current loop is given as:

$$\frac{i_L(s)}{i_L^*(s)} = \frac{K_I(1+sT_I)}{s^2 LT_I + sT_I K_I + K_I} \quad ....(1)$$

Comparing this with standard 2nd order system, we get,

$$K_I = 2\xi\omega_n L \text{ and } T_I = \frac{2\xi}{\omega_n} \quad ....(2)$$

5.0 DESIGN OF VOLTAGE-LOOP

Now, consider the voltage-loop of the inverter. Let the current-loop is ideal ($i_L = i_L^*$). The voltage controller controls the output voltage v_c by controlling i_c. Here, the load current acts as disturbance. The voltage controller needs to unnecessarily generate i_{LOAD}. The load current disturbance is compensated through load current-feedforward as shown in Figure 7 so that the controller needs to generate only i_c^*. The simplified voltage-loop of the inverter is given in Figure 8 which shows that it is free from the load current disturbance.

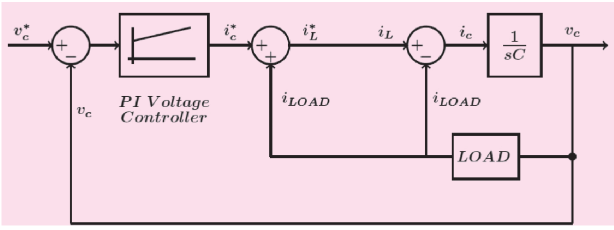

FIG. 7 LOAD CURRENT FEEDFORWARD CONTROL

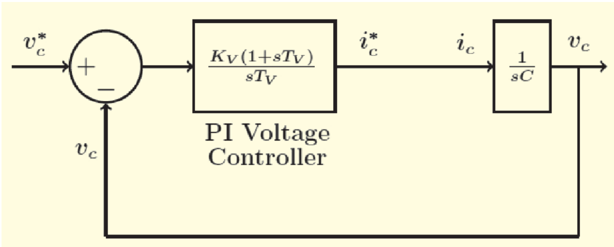

FIG. 8 SIMPLIFIED VOLTAGE-LOOP

The closed loop transfer function of the voltage-loop is given as:

$$\frac{v_c(s)}{v_c^*(s)} = \frac{K_v(1+sT_v)}{s^2CT_v + sT_vK_v + K_v} \quad ....(3)$$

Comparing this with standard 2nd order system, we get,

$$K_v = 2\xi\omega_n C \quad \text{and} \quad T_v = \frac{2\xi}{\omega_n} \quad ....(4)$$

We have to tune these parameters till the actual waveform exactly follows the reference waveform. The values of ξ and ω_n depend on the system's required settling time and the allowable peak overshoot.

6.0 SIMULATION RESULTS

The design parameters for the inverter are L = 580 mH, C = 4.7 µF, Switching frequency, f_{sw} =25 kHz. The simulation is done using MATLAB/ Simulink™ toolbox. The solver used is ode4 (Runge-Kutta) with fixed step size of 0.1 µs. The results are obtained with 1500 W load.

The output voltage waveforms of the inverter for non-linear (diode bridge rectifier with capacitor filter) as well as linear (R, RL and RC) loads are shown in Figure 9 to Figure 12.

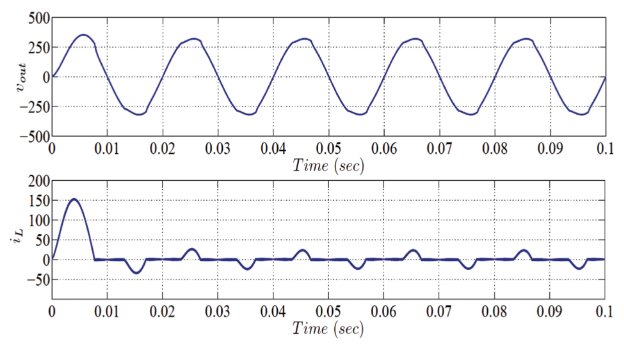

FIG. 9 INVERTER OUTPUT VOLTAGE WITH CONTROLLER FOR 1500 W NON-LINEAR LOAD

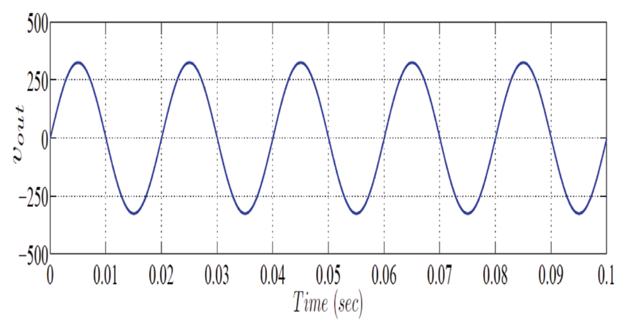

FIG. 10 INVERTER OUTPUT VOLTAGE WITH CONTROLLER FOR 1500 W RESISTIVE LOAD

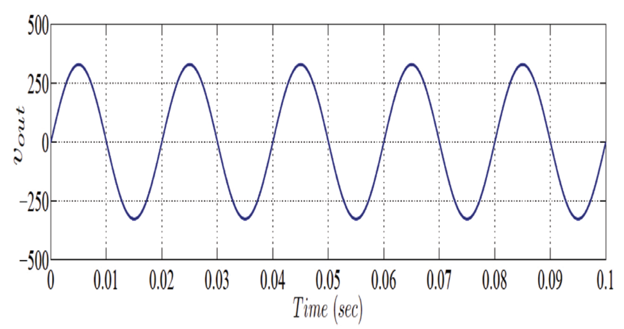

FIG. 11 INVERTER OUTPUT VOLTAGE WITH CONTROLLER FOR 1500 W 0.8 LAG LOAD

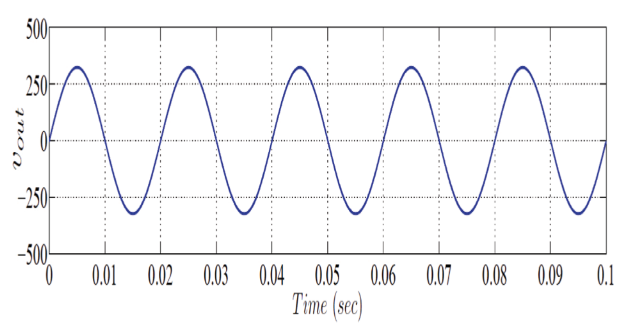

FIG. 12 INVERTER OUTPUT VOLTAGE WITH CONTROLLER FOR 1500 W 0.8 LEAD LOAD

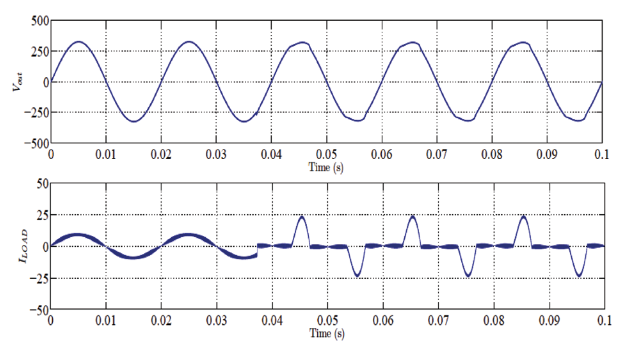

FIG. 13 INVERTER OUTPUT VOLTAGE WITH CONTROLLER WHEN LOAD IS SWITCHED FROM RESISTIVE TO NON-LINEAR LOAD FOR 1500 W

7.0 CONCLUSION

The output voltage waveform of the inverter with non-linear load is significantly improved when the controller is used. For any kind of load, even though there is sudden change in load, the output voltage of the inverter remains constant at the desired voltage with low THD value if the controller is used.

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