A SPWM CONTROLLED THREE-PHASE UPS FOR NONLINEAR LOADS

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ABSTRACT

This paper presents the design of a high-performance sinusoidal pulse width modulation (SPWM) controller for three phase uninterruptible power supply (UPS) systems that are operating under highly nonlinear loads. The classical SPWM method is quite effective in controlling the RMS magnitude of the UPS output voltages. However, it is not good enough in compensating the harmonics and the distortion caused specifically by the nonlinear currents drawn by the rectifier loads. The distortion becomes more severe at high power where the switching frequency has to be reduced due to the efficiency concerns. This study proposes a new design strategy that overcomes the limitations of the classical RMS control. It adds inner loops to the closed-loop control system effectively that enables successful reduction of harmonics and compensation of distortion at the outputs. Simulink is used to analyze, develop, and design the controller using the state-space model of the inverter. The controller is implemented in the TMS320F2808

DSP by Texas Instruments, and the performance is evaluated experimentally using a three-phase 10 kVA transformer isolated UPS under all types of load conditions. In conclusion, the experimental results demonstrate that the controller successfully achieves the steady-state RMS voltage regulation specifications as well as the total harmonic distortion and the dynamic response requirements of major UPS standards.

Index Terms: Inverter, Nonlinear Load, Sinusoidal Pulse Width Modulation (PWM) Control, Uninterruptible Power Supply (UPS).

I INTRODUCTION

The increased use of rectifiers in critical loads employed by the information technologies, and medical and military equipment mandate the design of uninterruptible power supplies (UPS) with high-quality outputs [1]–[3]. The highly nonlinear currents drawn especially by high-power single-phase rectifier loads greatly distort the UPS outputs. The distorted UPS voltages cause generation of low dc voltage at the output of the rectifier loads, which causes high current flow, increased power losses, and possibly the malfunction of the critical load or the UPS. The distortion is resulted mainly by the voltage drop across the inductive element of the LC filter due to the non-sinusoidal current at the output of the inverter [4]–[6]. In a UPS system, the inverter is responsible for synthesizing sinusoidal voltages from a dc source through the pulse width modulation (PWM) of the dc voltage.

The stationary or synchronous-frame space-vector PWM (SVPWM)-based controllers are the primary choice of many researchers and the applications currently used in industry, today [4], [7]. However, the classical sinusoidal PWM (SPWM) method is still preferred by many manufacturers because of its implementation simplicity, easy tuning even under load, flexibility, and most importantly the advantages of controlling each phase independently. The independent regulation of each phase provides easy balancing of three-phase voltages which makes heavily unbalanced loading possible. Also, it avoids problems such as transformer saturation. Although the classical SPWM method is quite effective in controlling the RMS magnitude of the UPS output voltages, it is not good enough in compensating the harmonics and the distortion caused specifically by the nonlinear loads.

One limitation of the PR method is the possible shifting of frequencies caused by the calculation errors when digitally implemented. For example, if 50 Hz or other harmonic components change frequency, the controller coefficients may need to be recalculated. And online calculation is not practical. In addition, the gain at the desired frequency may go to infinity. Therefore, a filter that has a little wider bandwidth must be designed. This reduces the gain. But, then there might be an interference of other frequencies. The harmonic droop method is another technique that has appeared also recently. If it is implemented effectively, it can eliminate all the harmonic distortions from the waveform. The harmonic droop method determines each harmonic component of the current through a fast Fourier transform and then applies a droop strategy to cancel the effect of these harmonics. In other words, harmonic droop method reduces the harmonics at the output by injecting harmonics into the voltage reference.

II CIRCUIT DESCRIPTION

The single-line diagram of a typical three-phase four-wire transformer isolated UPS system is given in Fig. 1. The three phase thyristor-based controlled rectifier converts the mains voltages into a constant dc and also provides standalone charge to the batteries. Then, a six-switch PWM voltage source inverter (VSI) creates balanced three-phase sinusoidal voltages across the load terminals at the utilization frequency and magnitude. The LC low-pass filter removes the harmonics generated by the PWM switching. The Δ-winding of the transformer blocks the third harmonic currents at the inverter side, and the zigzag winding provides a neutral point and zero phase difference for the load-side voltages.

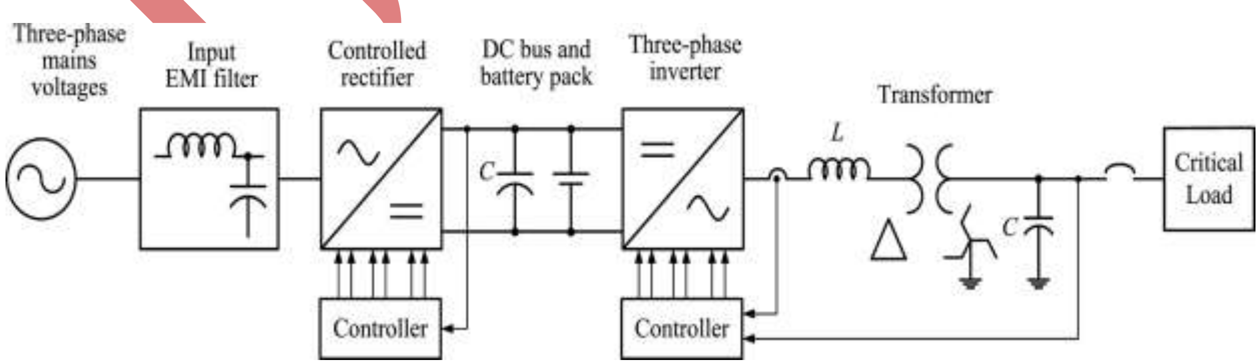

Fig. 1. Single-line diagram of a typical three-phase four-wire transformer isolated UPS system

The developed model is also used to study the controller performance for the lowest THD of the output voltage while maintaining the stability and a good dynamic response under all load conditions. The model is developed based on the circuit schematic given in Fig. 2. As shown in Fig. 2, an insulated gate bipolar transistor (IGBT)-based three-phase inverter is used to produce pulse-width modulated voltages across the terminals labeled as 1, 2, and 3. Moreover, L is the external filter inductor used to reduce ripple at the line current, L is the primary side leakage, and Lμ is the magnetizing inductance of the transformer; then Llk2 is the secondary side leakage inductance, Cis the filter capacitor, and finally R is the load resistance (the prime symbol represents the parameters referred to the Δ-side of the transformer).

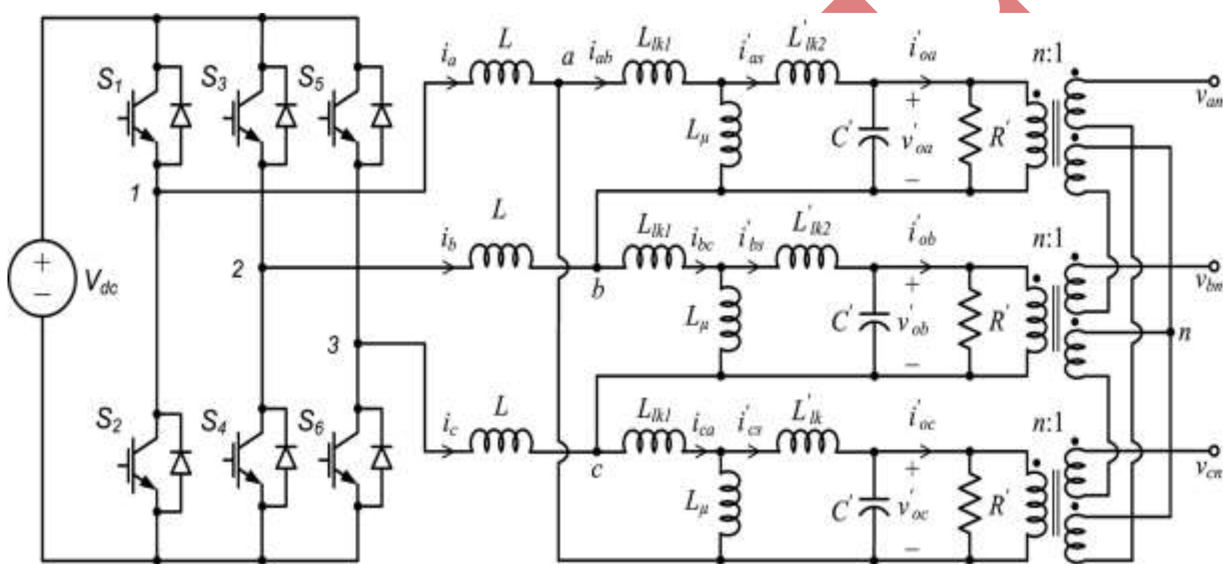

Fig. 2. UPS inverter stage including the Δ-zigzag transformer equivalent circuit and the resistive load

$$\begin{bmatrix} v_{12} \\ v_{23} \\ v_{31} \end{bmatrix} = \begin{bmatrix} \left(2L + L_{lk1} + \frac{L'_{lk2} L_\mu}{L'_{lk2} + L_\mu}\right) & -L & -L \\ -L & \left(2L + L_{lk1} + \frac{L'_{lk2} L_\mu}{L'_{lk2} + L_\mu}\right) & -L \\ -L & -L & \left(2L + L_{lk1} + \frac{L'_{lk2} L_\mu}{L'_{lk2} + L_\mu}\right) \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} + \frac{L_\mu}{L'_{lk2} + L_\mu} \begin{bmatrix} v'_{oa} \\ v'_{ob} \\ v'_{oc} \end{bmatrix}.$$

III CONTROLLER DESIGN

This section presents the design of the proposed inverter controller. The controller is based on the multi loop SPWM method as shown in Fig. 5, which is also shown as a block in Fig. 3. The controller topology is very similar to the classical state-feedback multi loop controllers [8], [9], except that all the loops are combined (instead of cascade connection) before they are applied to the PWM generator. This feature basically adds the relative benefits of each loop and creates a more effective multi loop strategy. In order to facilitate the understanding of the proposed controller, the reasoning behind the selected control topology can be explained as follows. The control system shown in Fig. 4 consists of one outer voltage loop and three inner loops. The outer loop is the main voltage loop, which regulates the fundamental frequency component of the output voltage and its steady-state RMS value using a PI compensator; for that reason, it has slower dynamics.

The first of the inner loops is the voltage reference feed forward loop which provides fast transient response but less benefit to the compensation of the harmonic distortions. The second inner loop is the voltage loop where the measured ac output voltages are instantaneously compared to the reference ac voltages created by the main loop and the error (Error1) is found; then the loop is compensated using a PD controller. This loop is responsible for correcting the phase shift and improving the waveform quality of the output voltages. The simulation results confirm that the gain Kp2 controls the THD of the voltages effectively and improves the waveform quality. The dynamic characteristic of this loop is relatively fast since there is no integrator. Actually, the fast dynamic with high gain is desired since it generates the corrective control actions to compensate for the distortion caused by the nonlinear currents, but this feature easily pushes the system into instability. One solution to this problem is to add a derivative control; however, it provides a minor help to stabilizing the system.

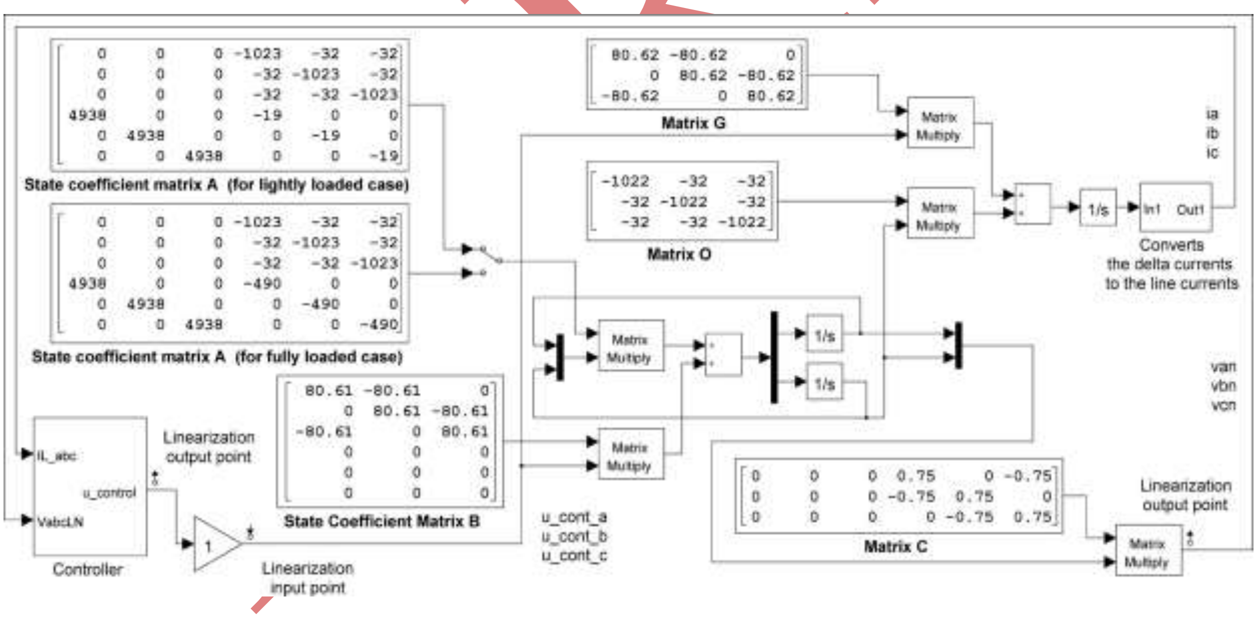

Fig. 3. State-space model of the inverter power stage (the plant) including the closed-loop control system and the controller built in Simulink

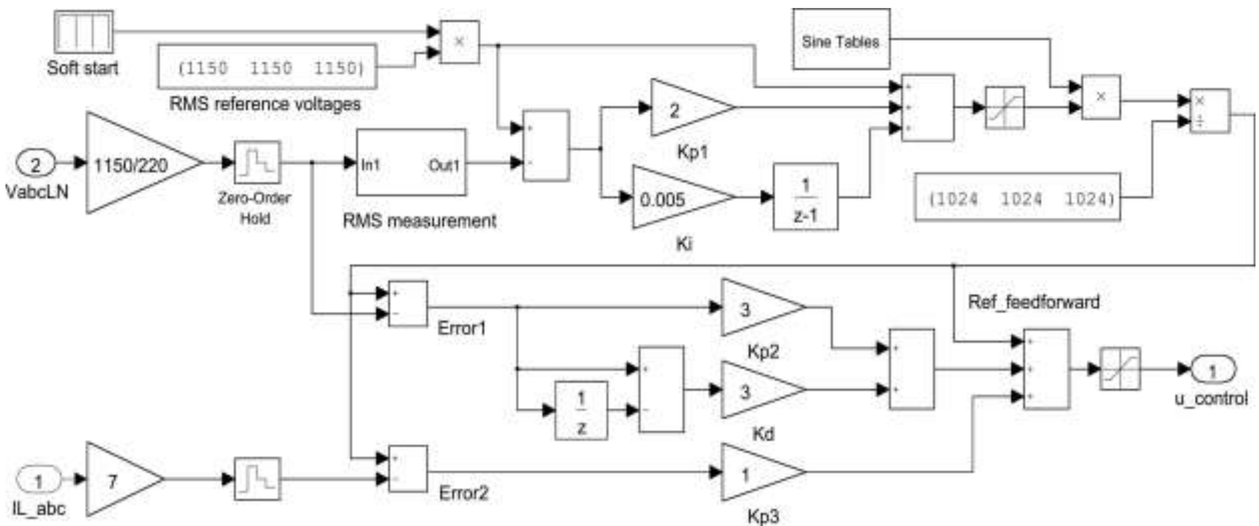

Fig. 4. Simulink model of the proposed multi loop controller

IV SIMULATION DIAGRAM AND RESULTS

The simulations are done in the MATLAB/Simulink environment using the Simulink and PLECS model of the inverter and the controller as shown in Fig. 5. The results are evaluated based on steady-state error, transient response, and the THD of the output voltage. Fig. 6 shows the RMS value and the percent THD of the output voltage versus three different loads. According to Fig. 6, when the linear load at 8.5 kW is applied, the controller achieves 0.3% THD, and similarly when the nonlinear load at 10 kVA is applied, the controller achieves 3.1% THD. In addition, the RMS voltages are very well regulated at 220 V for each phase with an excellent transient response for the linear load but a fair response for the nonlinear load case.

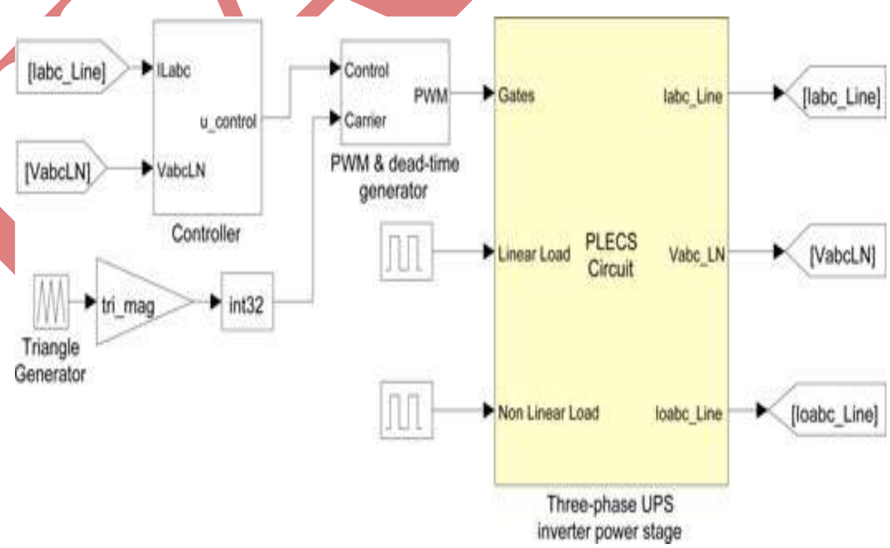

Fig. 5. Simulink Model of the Inverter System

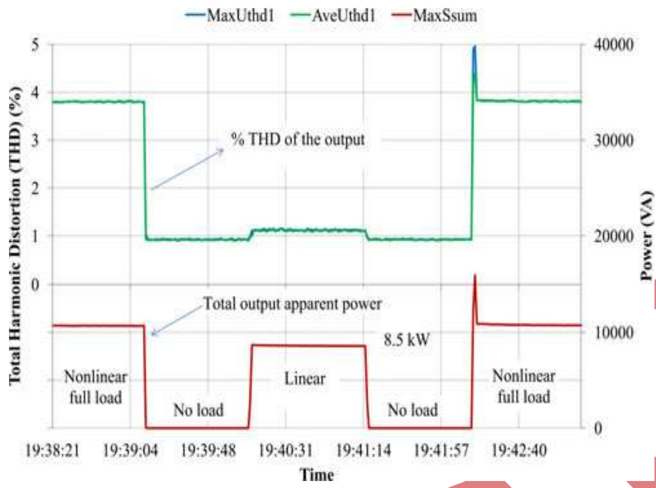

Fig. 9. RMS fluctuations (top trace) and the profile of the percent THD of the output voltages (second trace) versus the load delivered by the inverter (bottom trace)

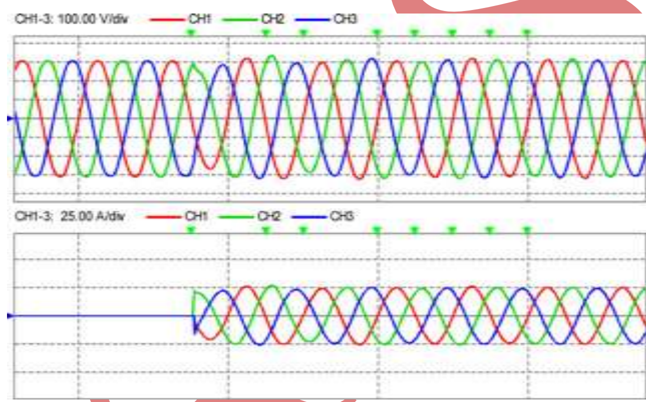

Fig. 10. Measured transient response of output voltages (upper trace) and currents (lower trace)

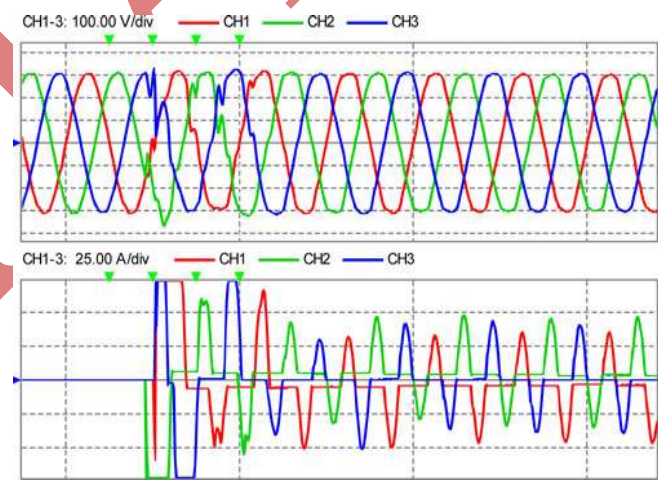

Fig. 11. Measured three-phase output voltages and the load current of one phase for the following four cases

V CONCLUSION

This paper presents the analysis and design of a high performance SPWM controller for three-phase UPS systems powering highly nonlinear loads. Although the classical SPWM method is very successful in controlling the RMS magnitude of the UPS output voltages, it cannot effectively compensate for the harmonics and the distortion caused by the nonlinear currents drawn by the rectifier loads. Therefore, this paper proposes a new strategy with a new design that overcomes the limitations of the classical RMS control. It adds inner loops to the closedloop control system effectively that enables successful reduction of harmonics and compensation of distortion at the voltages. The controller performance is evaluated experimentally using a three-phase 10 kVA transformer isolated UPS. A THD equal to 3.8% at the output voltage is achieved even under the worst nonlinear load. The load consists of three single-phase rectifiers connected between each line and the neutral and absorbing power equal to the rated power of the UPS with a crest factor up to 3. In conclusion, the experimental results demonstrate that the proposed controller successfully achieves the steady-state RMS voltage regulation specification as well as the THD and the dynamic response requirements of major UPS standards.

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