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"Design of Three Phase UPS system using Multi-Loop Fuzzy Logic Controller for Linear and Non-Linear Loads"

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Abstract

This Paper proposes 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. 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 classical SPWM method and space vector modulation are quite effective in controlling the RMS magnitude of the UPS output voltages but couldn't effectively compensate the harmonics and distortions caused specifically by the nonlinear loads. The distortion becomes more severe at high power where the switching frequency has to be reduced due to the efficiency concerns. It adds inner loops to the closed loop feedback control system effectively that enables successful reduction of harmonics and compensation of distortion at the outputs. The fuzzy based multi-loop controller eliminates the periodic errors on the output voltages due to inverter voltage nonlinearity and load disturbances.The steady-state RMS voltage regulation, total harmonic distortion and dynamic performance of the three-phase UPS is investigated in detail. The theory of the control strategy is analyzed by means of simulink using the state-space model of inverter.

Keywords:

uninterruptible power supply (UPS), nonlinear load, sinusoidal pulse width modulation (SPWM) control, resonant controller and fuzzy logic controller (FLC)..

1. Introduction

In the modern world, electricity has an indispensable role with its ability to combine power and intelligence. Most of the systems which are located in critical points in daily life need electricity to operate. The electrical energy increases productivity, efficiency, and allows a high degree of safety, reliability, and comfort of life. Contingency in the electric power line cannot be accepted critical areas involving safety, security, continuous industrial processes, data protection in information technologies. Although in the past backup generators were satisfactory to get power in case of interruption in the utility, long delay of generator starting and switching in today is not acceptable. Such delays badly affect critical loads such as computers, internet providers, telecom service providers, etc. as the power interruption causes data loss, process failure, and the cost for recovery becomes unacceptable. Even though the electric utility industry has made great effort for uninterrupted power line and undistorted line voltage, inevitably still there exist problems such as distortions, sag, swell, and spikes.

In order to avoid such problems, uninterruptible power supply (UPS) systems [2]-[5], [7]-[36] with continuous and clean output power are utilized by compensating the harmonics and distortions caused by specifically nonlinear loads by implementing certain suitable and efficient control techniques. In this paper, output voltage control of a UPS with a zig-zag connected transformer is investigated. Although there exist many papers on the output voltage control of UPS, minority of them involve the transformer based UPS. Due to the difficulty in modeling the zigzag transformer and uncertainty in the parameters of transformer, model based control algorithms which are the methods discussed in most papers, are not directly applicable to the transformer based UPS. Thus, instead of model based control structures, self converging feedback control structures are investigated. Among various control techniques, synchronous reference frame control (SRFC), resonant filter type control (RFC), and repetitive control (RC)[14]-[21] are found suitable for application to the transformer UPS. However, due to the complexity of the above techniques, only the multi-loop high-performance SPWM control strategy method is considered suitable for the low cost (in terms of control, measurement etc. cost) and/or high power UPS systems. Therefore, the multi-loop high performance SPWM and its application to the three-phase transformer based UPS system will be the main focus of this paper.

The aim of the paper is to establish in depth background on the multi-loop control method and apply the knowledge to systematically design the output voltage controller of the three-phase transformer based UPS. With the design issues well understood and a proper design completed, the performance of such a system will be investigated in detail with linear and non linear loads [28],[29] to evaluate the feasibility of this technology. To combine multi-loop controller with an advanced controller to control the output voltage to obtain THD levels much less thereby improving the quality of output delivered to the load. Therefore, the main contribution of this thesis is towards high performance multi-loop controller design and detailed performance investigation of a three-phase transformer based UPS system. The stationary[1] 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 [28], [29]. For example, the total harmonic distortion (THD) is greater than 5% limit even with good filtering. It becomes more severe at high-power UPSs where the switching frequency has to be reduced due to the efficiency and heating problems. This study proposes a multi-loop high-performance SPWM control strategy and a design that overcome the limitations of the classical RMS control. It adds inner loops to the closed loop feedback control system effectively that enables successful reduction of harmonics and compensation of distortion at the voltages. The simulation results using the proposed controller achieves THD less than 3.0% under the nonlinear load having a crest factor of 3 and absorbing power equal to the rated power of the UPS. However, the significance of the proposed multi-loop controller compared to other methods is as follows [1]: 1) The execution time is less and allows higher switching frequencies. The complex control algorithms take longer execution times and may limit the upper boundary of the switching frequency where you have actually some allowance for higher switching frequency operation [36]. Examples to the complex controllers are the repetitive, predictive, and harmonic droop controllers. 2) *The cost is low*. Some control algorithms require precise floating point calculations either because they depend on a precise model or they use frequency-dependent sensitive controller gains. In brief, the precision dictates use of high-performance floating point expensive microcontrollers. The current implementation of the proposed controller is using fuzzy logic controller. 3) *The easy tuning even under load*: Some are robust to this kind of tuning and some may not. This feature is preferred by some manufacturers. The easy tuning of the proposed method under load can be done with this method. 4) *The flexibility*: It means that you can modify your controller and optimize it according to the customer specifications at the time of installation or later in use. The optimization may include obtaining the lowest THD or the best tracking of the RMS value or the fastest dynamic response. So, the controller should be flexible anytime to do any of the aforementioned optimizations without significantly affecting the others. We have also verified this feature experimentally. 5) *The scalability*: It means that the controller is easy to design and tunable for any power level. Accordingly, this paper favors the proposed multi-loop controller using fuzzy logic controller and presents the work according to the following arrangement. Section II provides a short description of a typical three phase UPS system[1]. Then, the analysis of the inverter power stage and obtains the state-space model of the inverter is shown in Section III. The modeling is followed by the inverter power stage design in Section IV. The control system design is presented in Sections V. Section VI presents the simulation results and the conclusions are given in Section VII.

II. SYSTEM DESCRIPTION

The single-line diagram [1] 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. The load can be a three-phase or a single phase load ranging from linear to nonlinear load with a crest factor up to 3. The UPS uses a multi-loop controller implemented in fuzzy logic controller.

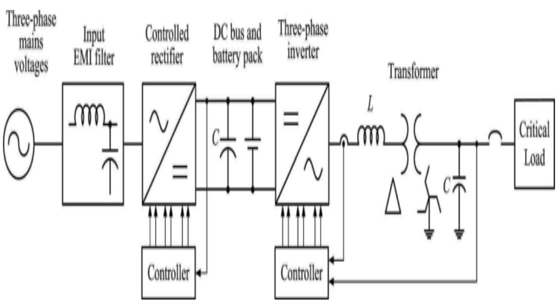

Fig.1 Single-line diagram of a typical three-phase four-wire transformer isolated UPS system

III. ANALYSIS OF THE UPS INVERTER POWER STAGE

The conventional three-leg three-wire inverter is commonly utilized in three-phase UPS applications. This inverter topology is generally used with a three-phase isolation transformer with Δ/Y (Δ/Z) winding connection in UPS applications. For feeding single-phase loads from a three-phase UPS, the Δ/Y (Δ/Z) connection of the transformer provides neutral terminal from the midpoint of Y (Z) connected secondary windings. A zero sequence current flows if the summation of the three-phase load currents is not zero. Single-phase loading of the UPS is the major reason of zero sequence currents. If a current path is not provided, zero sequence currents passes through the output capacitors of the UPS. This causes imbalance at the output voltages of the UPS. In such a transformer configuration, zero sequence currents circulate in the Δ connected primary windings. Thus, a three leg three-wire inverter can be utilized in UPS systems employing a transformer with Δ/Y (or Δ /Z) connection. The isolation transformer also provides galvanic isolation. This section obtains the state-space model of the inverter stage of a three-phase UPS in order to design the controller for the inverter. 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. of this project is to develop a fuzzy logic based multi loop controller to a three phase UPS to yield high performance by lowering the Total harmonic distortion and by regulating the RMS voltage magnitude under nonlinear load conditions.

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 [1] Fig. 2. an insulated gate bipolar transistor (IGBT)-based three-phase inverter is used

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to produce pulse-width modulated voltages across the terminals labeled as 1, 2, and 3.

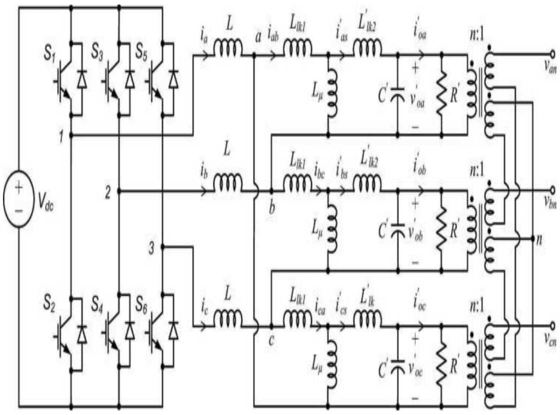

Fig.2 UPS inverter stage including the Δ-zigzag transformer equivalent circuit and the resistive load.

Writing the voltage equations[1] at the Δ-side of the transformer yields the following sets of equations for the line-to-line voltages across the inverter terminals, (1) as shown at the bottom of the page. Similarly, writing the current equations yields the following sets of equations (1) to (13), [1] for the derivative of the transformer secondary currents. The state-space model of the proposed inverter design is given in the next section after the design parameters are determined based on the given specifications. IV. STATE-SPACE MODEL OF THE INVERTER POWER STAGE The state-space model of the three-phase inverter is needed to develop and test the controller performance. So, by calculative assumptions the values of L = 30 μH, Lμ = 1 H, Llk1 = 820 μH, Llk2 =100 μH, C' = 202 μF, Vdc =405 V, Vtri = 2487, R' = 10 Ω for full load and R' = 255 Ω for the light load in the set of equations obtained through modeling of three phase inverter ,the state space matrices are being calculated. By means of the state-space matrices the state space model of the inverter is obtained. Hence by substituting the desired values in the equation from(3.1-3.6) the following state matrices are being obtained.

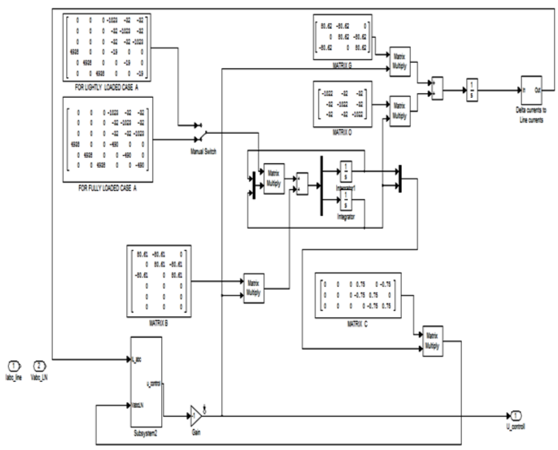

Fig.3 state space model of inverter power stage in three phase UPS

V. DESIGN OF MULTI LOOP CONTROLLER

The controller topology is very similar to the classical state-feedback multi loop controllers 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

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Volume 03 Issue 10
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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.

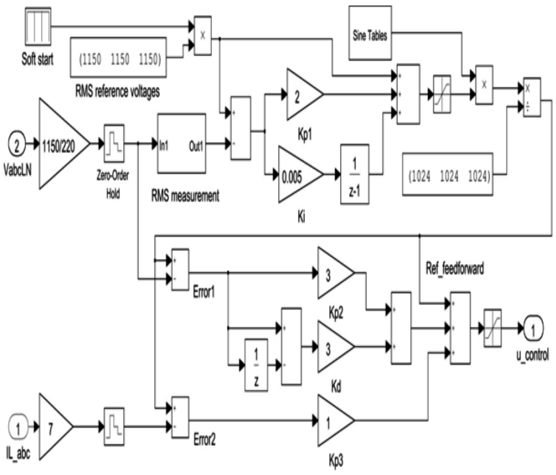


Fig.4 Simulink model of the proposed multi loop control diagram

The study of 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. The more effective solution is to add an ac current inner loop which provides the feedback about the voltage drop across the inductive element of the *LC* filter, which makes the part of the compensation against the harmonic distortions at the voltage. In this loop, the measured inductor currents are instantaneously compared to the reference currents created by the main loop and the resulted error (Error2) is combined to the main control output after it is multiplied by the gain Kp3, as shown in Fig. . Our studies have shown that the ac current loop with the gain Kp3 stabilizes the control system effectively. In addition, the inductor currents that are measured for the closed-loop control are also used for overload protection and current limiting purposes. So, the cost of the current transformers is justified in this design. The advantage of the multi-loop control system proposed here is that the loops can be optimized for the best performance relatively independent of each other.

VI. SIMULATION RESULTS

The simulink model of the proposed multi-loop controller is built in Matlab simulation environment and performance is evaluated based on the RMS voltage and Total harmonic distortion (THD).The inverter power stage being heart of the UPS is being designed as sub circuit of the UPS and the state space model of the inverter that constitutes for stability is also designed and the control diagram is designed such that it is in line with the state space model of the inverter power stage of UPS.

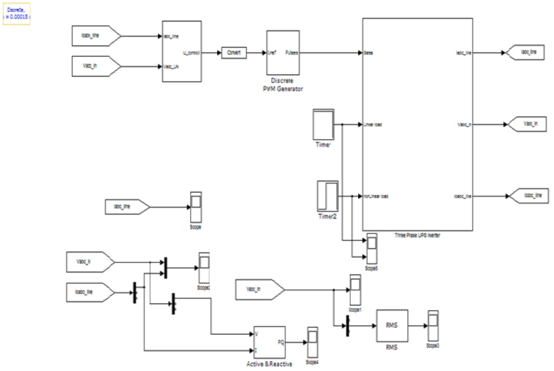


Fig.5 Simulation circuit of Three phase UPS with multi loop SPWM controller

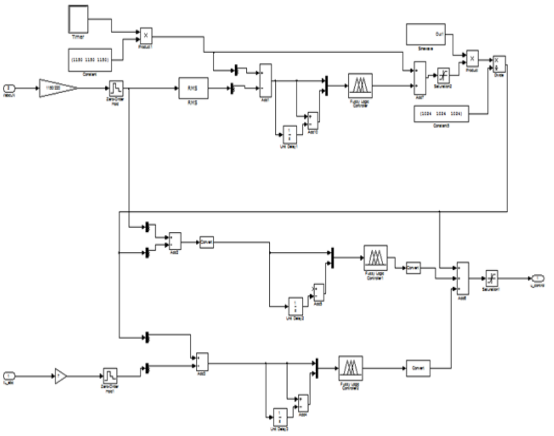


Fig.6 fuzzy based multi loop simulation control circuit

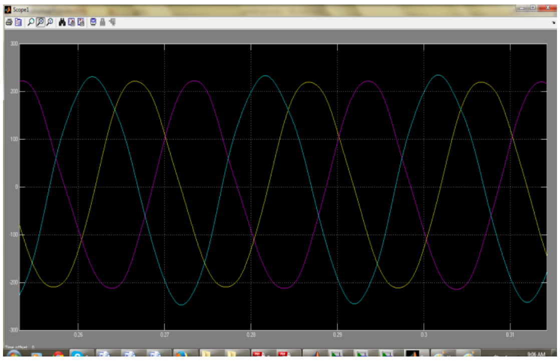


Fig.7 Three phase voltage under Linear loads

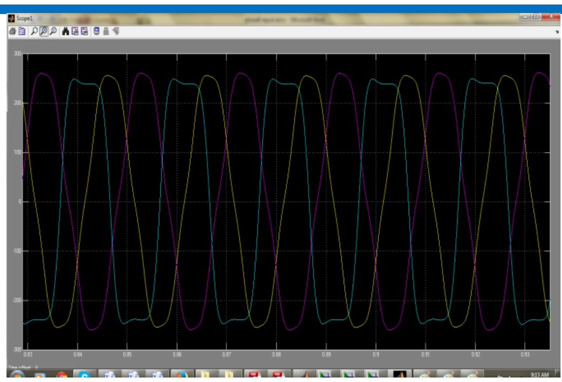


Fig.8 Three phase voltage under non Linear loads

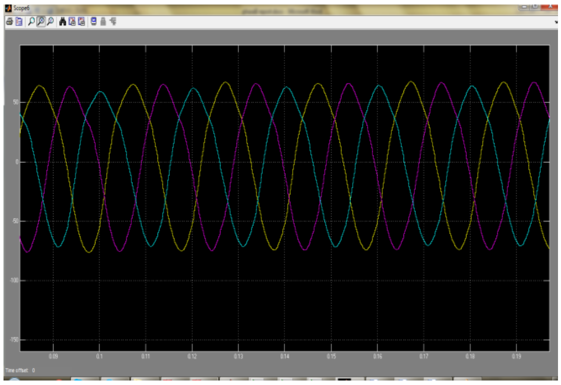


Fig.9 Three phase line current under linear loads

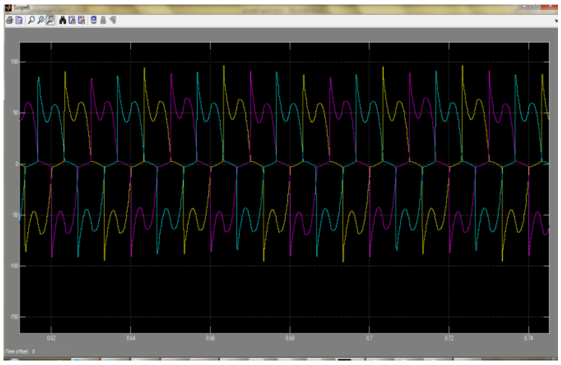
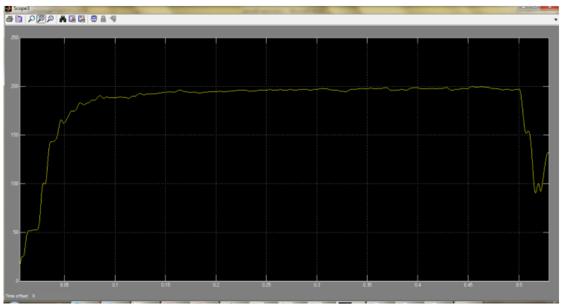


Fig.10 Three phase line current under non linear loads



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Volume 03 Issue 10
June 2016

Fig.11 RMS load voltage for linear loads

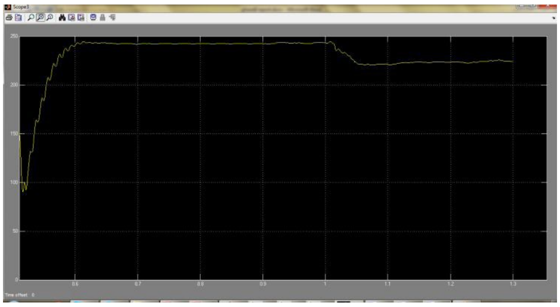

Fig.12 RMS load voltage for non linear loads

VII. CONCLUSION

SPWM controller for three-phase UPS systems powering highly nonlinear loads with a fuzzy based multi loop control is implemented in the project. 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 project proposed a new strategy of fuzzy based multi loop design design 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 voltages. The controller performance is evaluated using a three-phase 10 kVA transformer isolated UPS. THD value equal to 2.85% at the output voltage is achieved even under the worst nonlinear load.

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