Study and Simulation of Single-Phase to Three-Phase UPF System for Agricultural Applications

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Abstract - **This paper describes simulation and design of single-phase to three-phase UPF system for agricultural/ household applications. The average current mode control (ACMC) technique is used for Unity Power Factor (UPF) correction of single phase AC-DC boost converter. A comprehensive study and analysis of single-phase to three-phase converter with UPF operation is presented. Closed loop control of single phase AC-DC UPF boost converter is designed. The three phase voltage source inverter with Sinusoidal Pulse Width Modulation (SPWM) technique has been used for dc to 3-phase ac conversion. The voltage mode control of three-phase voltage source SPWM inverter have been designed and simulated. The complete system with the integration of single-phase and three-phase converter has been simulated. The simulation results with their performance such as power factor (pf), Total Harmonic Distortion (THD) and efficiency have been analysed. The simulation results on resistive load is presented in this paper.**

Keywords – **Average current mode control, Sinusoidal pulse width modulation, Total harmonic distortion, Unity power factor correction.**

I. INTRODUCTION

Most of the rural areas are supplied by single-phase electrical systems. Single-phase electrical distribution systems are less expensive to install than three phase distribution systems. But it can only be used for low power applications such as lighting, home appliances etc. The electrical equipment whose motor size is about 5 Hp, single-phase supply is usually adequate. Beyond that, appliances are usually designed to run on three phase power. The rural/agricultural applications such as motors to operate irrigation pumps, grain handling systems, large air compressors, refrigeration units etc. are designed to run on three phase supply but in general single phase supply is available in the rural areas.

Generally, electrical and electronics equipment are supplied by 50Hz utility power supply. The power systems of these equipment are processed through power converters. For agricultural and household applications, popular topology/technique is the use of a single-phase front-end rectifier with DC-DC boost converter followed by a 3-phase inverter with a filter in star or delta connection. But as the power levels increases it has its own drawbacks such as, poor power factor (pf), high harmonic distortion on AC mains current, unregulated output bus voltage and losses, overheating in input side transformers, shunt/output capacitors, power cables and in the ac machines.

Due to undesirable power factor, the peak current in input side increases and it requires larger devices and larger wire size. This increases the weight, volume and overall cost of the system. It does not meet the requirement of IEC 61000-3-2 and IEEE-519 standards for Total Harmonic Distortion (THD) and power factor in the electrical equipment.

The single-phase to three-phase conversion technique using rotary and static phase converters have its pros and cons when used in high power applications. The conventional technique for unity power factor correction is the front-end rectifier followed by boost converter. But this type of converter endures high conduction as well as switching losses due to hard switching of the devices [1].

The front end rectifier with resonant converters scheme such as parallel resonant converters, quasi-resonant converters etc. were proposed in many literatures. But due to variable switching frequency and resonant behavior of current and voltage waveforms, these converters involve high circulating energy, which increases the conduction losses. The variable frequency creates problem for magnetic design, Electromagnetic Interferences (EMI) and output filter capacitor design [2, 3].

The power converters for low power and high efficiency have advanced from pulse width modulated converters to resonant converter and soft switching converters. But due to presence of parasitic, higher switching frequency and hard switching condition, the PWM converter suffers from high switching losses and switching stress in the circuits [4]. For reducing switching losses, there are other techniques [5] which achieve soft switching operation with the help of commutation circuits and auxiliary switches. It reduces the switch losses and EMI to some extent. But the conduction loss is still present in the circuit. Their efficiency is very poor which is not suitable for high power applications.

Various active and passive power factor techniques have been proposed in literature [6, 7]. These technique control the quantity of power drawn by the load in order to get unity power factor and low harmonic content in the input AC current. But active unity power factor correction technique is unable to reduce the switching loss and conduction loss in the switching devices/elements. It also draws huge pulsating current due to direct connection of diode and output electrolytic capacitor. For higher power application the efficiency and power factor of these converters are very low and thus are not suitable for agricultural and rural applications.

The topology to increase the overall system efficiency is introduced [8], where an inductor is placed at the input side to filter out the EMI present in the system. It uses two diodes and two switches as a rectifier followed by DC-DC boost UPF converter. It reduces the conduction losses. But it has significant commutation losses in the conducting switches and in the diodes due to hard switching of the switches. Bridgeless boost PFC is also used for high power efficiency applications. It uses two semiconductor switches for conduction path and two boost inductors in the input side. This type of converter is suitable for medium-to-high power applications. But, due to the switching losses in the two switches, efficiency of bridgeless boost converter is poor and the presence of two inductors at the input side increases the volume of the complete system. It also has large common mode EMI in the input side and low power factor [9, 10].

Single phase AC-DC PFC zeta converter also finds application in high power requirement [11]. For high power applications only CCM mode can give good performance in this converter. Since, it uses high frequency transformer to provide isolation at the output stage. Its major drawbacks are high switching losses due to front end rectifier in the input side, higher cost and increased size. This converter is suitable for low power applications.

The quasi-resonant circuit can be used for low power applications, which achieves soft-switching without additional active switches [12]. But this needs to be controlled by frequency modulation and not by pulse width modulation. Another disadvantage of quasi-resonant type converter is high current and voltage stress on main conducting devices and diodes. For soft-switching operation Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) techniques have been proposed [13, 14]. These incorporate boost PWM converter and resonant technique to achieve soft switching with nearly unity power factor correction and low harmonic in input grid current. Soft switching converter uses resonant technique to soften the switching transition. This results in reduction of the switching losses. The soft switching is achieved by addition of Zero Voltage Transition (ZVT) circuits. Due to lower switching losses, these types of converters are useful for medium-to-high power applications. A resonant branch is used in the ZVT DC-DC boost converter to achieve soft switching [15, 16]. At switching commutation, the resonant branch is energized to create a partial resonance to achieve ZVS or ZCS. The resonance occurs during switch transition. This limits the auxiliary circuit conduction losses. After switching, the resonant network is disabled in such a way that the normal operation of the PWM converter continues for maximum part of the switching cycle. By doing this, the PWM converter can achieve soft-switching without increasing the voltage and current stresses on the main conducting switches.

For dc-ac conversion, three-phase voltage source inverter (VSI) with sinusoidal pulse width modulation (SPWM) techniques is proposed by many researchers [17, 18]. Large number of PWM topologies are presented to obtain the variable voltage and frequency output using three-phase VSI [19]. VSI using PWM technique can provide excellent dynamic and steady-state performances at various load and transient conditions for high power ac drive applications [20].

In the ac motor drive applications the SPWM based three-phase inverters are widely employed. The carrier based PWM techniques are also being used in many three-phase SPWM inverters due to its constant switching frequency, low ripple current and clear harmonic spectrum characteristics [21]. Another PWM technique for three phase VSI is Space Vector Pulse Width Modulation (SVPWM), which has high voltage utilization ratio as well as ease of digital realization [22].

The carrier based modulation and SVPWM topologies are the widely used approach for three-phase VSI for high power applications. Since it has low harmonic distortion characteristics, fixed converter's switching frequency and ease of realization in hardware [23].

To analyze the switching loss a discontinuous SVPWM techniques for three-phase VSI supplying two-phase load is presented [24]. A robust and advanced SVPWM based predictive current controller to mimic the deadbeat control in the synchronous d-q frame is presented [25], which has robust design with ease of digital implementation.

The proposed system for rural application consists of IGBT based single-phase AC-DC PFC converter and six-switch three-phase SPWM VSI. Average current mode control (ACMC) technique is used to achieve unity power factor. Simulation and steady state response at resistive load with their performance such as power factor, harmonic content and efficiency have been evaluated and analyzed in this work.

II. SYSTEM DESCRIPTION

The power conversion and control industries are focusing on design of power efficient electrical equipment for improved power quality standards for variety of applications. In these systems, each stage of the system needs to be designed with high efficiency and robust control. The schematic diagram of single-phase to three-phase system is shown in figure 1.

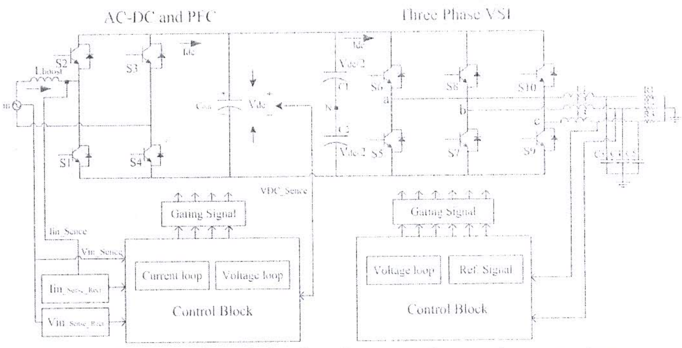

Fig.1. Schematic of single-phase to three-phase system

First stage represents single phase AC-DC converter followed by boost PFC with gating signal. The input supply (V_{RMS}) is rectified and boosted at required dc voltage (V_{dc}). The second stage includes three phase SPWM inverter followed by LC filters. Regulated dc voltage (V_{dc}) from the first stage is the input for three phase VSI SPWM inverter. Three-phase control is designed to regulate the three-phase SPWM VSI output voltage ($V_{L-L(RMS)}$) irrespective of the variation in dc input voltage.

III. DESIGN AND CONTROL CONFIGURATION

The specifications of single-phase AC-DC to three-phase SPWM VSI system is presented in table I.

TABLE I

Specifications of the Single-phase to Three-phase System

Parameters	Ratings
Input AC voltage (V_{RMS})	(200-240)VAC
Rated output power (P_{out})	5kW
Line frequency (F_{Line})	50Hz
Targeted Power factor (pf)	0.99
Single phase output voltage (V_{dc})	650VDC
Targeted THD	$\leq 5\%$
Three phase inverter output (V_{L-L})	385VAC

A. IGBT based Front-End Rectifier

The IGBT based front-end rectifier is a PWM continuous conduction mode single phase AC-to-DC PFC converter. It consists of boost inductor (L_{Boost}), four IGBT switches (S1-S4) and dc filter capacitor (C_{out}). In each half cycle, the converter works as a boost PFC DC-DC converter.

B. Average Current Mode Control (ACMC)

The ACMC is one of the standard techniques used in industry today for AC-DC boost PFC converters. ACMC is a two-loop control technique viz. inner and outer control loop. The outer control loop is used to regulate the DC output voltage irrespective of variations in input supply. Schematic diagram of ACMC is shown in figure 2.

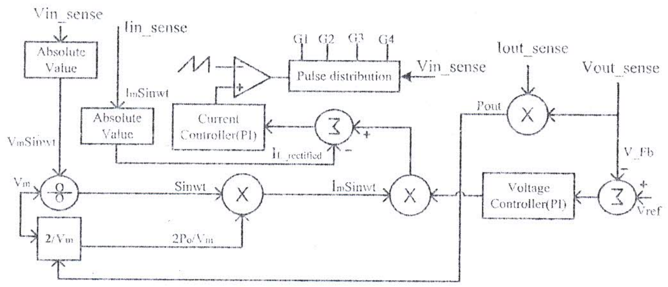

Fig.2. Schematic diagram of average current mode control

The inner loop produces a control output such that the inductor current follows the reference current. The voltage feed-forward loop is used to maintain constant output power as determined by load regardless of variations in input voltage. Switching pattern in each half cycle is shown in figure 3.

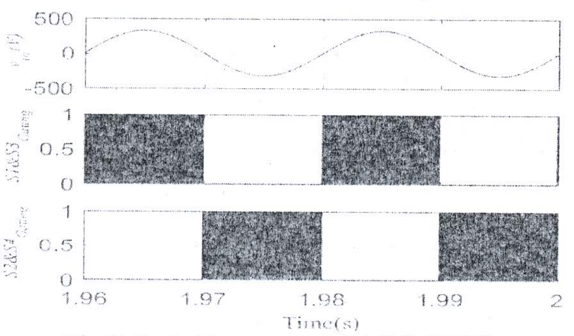

Fig.3. Switching pattern of AC-DC PFC converter

C. Six-Switch Three-Phase VSI

The three-phase ac output voltages of variable magnitude and variable frequency can be produced by six-switch based three-phase SPWM VSI [26]. It consists of two input capacitors (C1 and C2), six IGBT switches (S5-S10), three output filter inductors (L1-L3), three output filter capacitors (C3-C5) and resistive load. The LC filter has been used as a low pass filter in three phase VSI and it is formed by connecting three single phase LC filter into star configuration.

For ease of control, the rotating signals have been transformed to steady signal by abc to dq0 transformation. The d and q component of the voltages are independently controlled. The gating signals are generated and given to the six switches (S5-S10) properly. The schematic diagram of control loop for three-phase SPWM VSI is shown in figure 4.

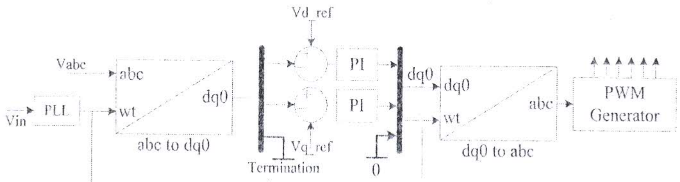

Fig.4. Closed loop control diagram of three-phase VSI

The switching pattern of six-switch based three-phase SPWM VSI is shown in figure 5.

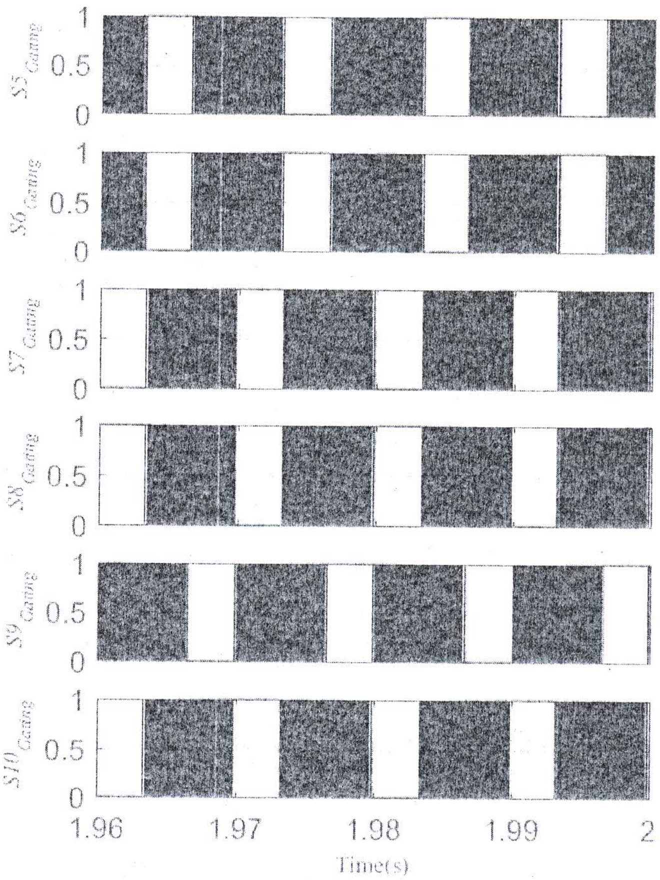

Fig.5. Switching pattern of three-phase SPWM VSI

IV. SIMULATION MODEL AND RESULTS

The single-phase AC-DC PFC to three-phase SPWM VSI for agricultural application has been simulated in the MATLAB-Simulink-based environment for validation of proposed design. The designed component values used in the simulation is presented in table II.

TABLE II

Design Parameters for Simulation

Components	Value
Boost Inductor (L_{Boost})	6mH
DC filter capacitor (C_{out})	3mF
Three-phase input filter capacitor (C_1 and C_1)	470uF
AC filter inductance (L_{filter})	3mH
AC filter capacitor (C_{filter})	10uF

The MATLAB-Simulink model consists IGBT based single-phase AC-DC PFC, three-phase SPWM VSI and their control algorithm. The simulation model of single-phase AC-DC PFC to three-phase SPWM VSI system is shown in figure 6.

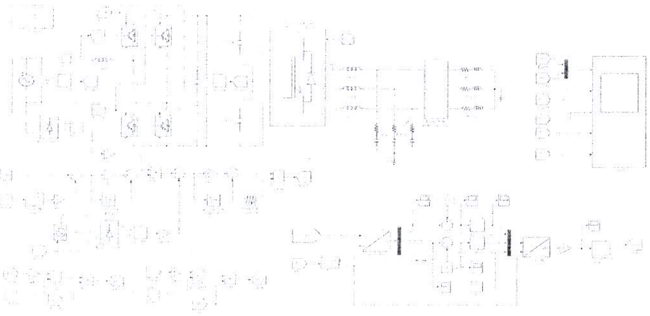

Fig.6. Simulink design of single phase to three phase system

The obtained simulation results at resistive dummy load are presented. The harmonic spectrum of grid input current is shown in figure 7 and the observed THD is 4.04 % which is well below the specified limit in IEEE-519 standard.

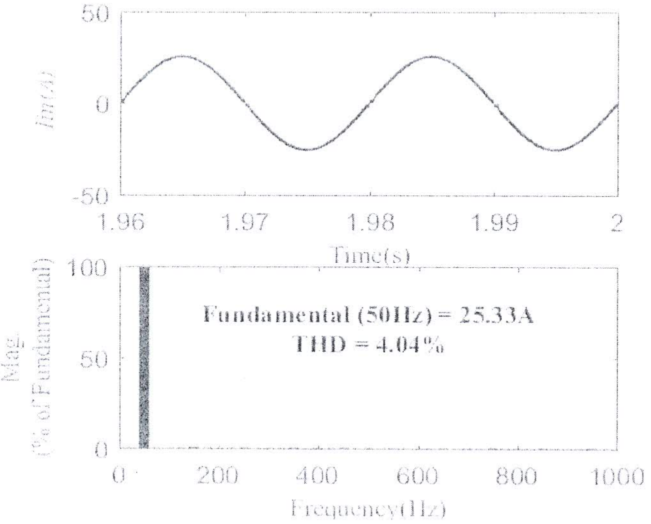

Fig.7. Harmonic spectrum of input current for PFC converter

The steady state response of IGBT based single-phase to three-phase SPWM VSI for agricultural application at resistive load is simulated and results are presented in figure 8.

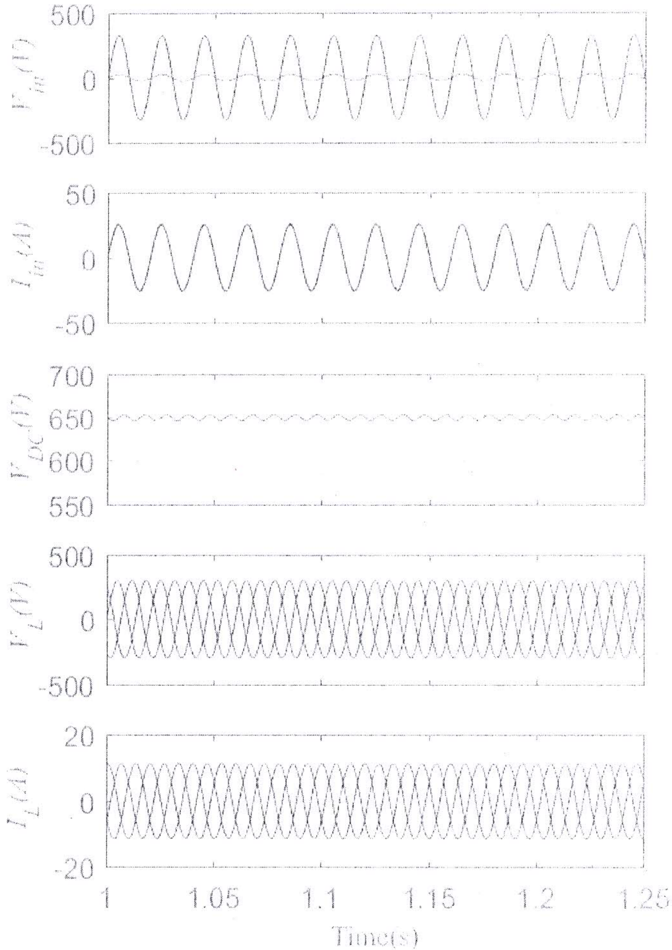

Fig.8. Output response of single phase to three phase system

CONCLUSION

A comprehensive analysis and simulation of IGBT based single-phase AC-DC PFC to three-phase SPWM VSI system for agricultural applications is presented. ACMC technique operating in continuous conduction mode is used for PFC converter stage. It is shown that the switching losses can be minimised by using ZVS or ZCS techniques in the PFC converter. The output DC voltage (V_{dc}), power factor and harmonic contents produced in PFC converter are evaluated and analysed. Sinusoidal three phase output is produced using SPWM techniques. The overall system stability and control performance in steady state operation are observed and evaluated on a dummy resistive load. DC bus voltage utilization can be increased by using SVPWM technique in three-phase voltage source inverter.

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