Power Factor Improvement Using PQ Theory Based Hybrid Controller for Three Phase Converter

M.Abitha Thangam and Dr.V.Gopalakrishnan

Abstract—**Three-phase controlled rectifiers have a wide range of applications, from small rectifiers to large High Voltage Direct Current (HVDC) transmission systems. It can handle reasonably high power and has acceptable input and output harmonic distortion. Harmonics present in the three phase converter is the major issue while it is been connected to the electric power distribution system. As the conventional model uses real time switching control, this paper deals with discrete event switching control based on hybrid system theory considering Lyapunov stability. Use of hybrid Controller is new to power electronic applications and hence the converters can provide input currents without distortion and with the unity power factor.**

Keywords— **Harmonics, Discrete Event Switching Control, Hybrid controller, Lyapunov Stability**

I. INTRODUCTION

Diode rectifiers are widely employed in industrial fields and consumer products thanks to advantages of low cost, simple structure, robustness and absence of control. However, this type of converters results in only unidirectional power flow, low input power factor, high level of harmonic input currents, malfunction of sensitive electronic equipment, increased losses and also contributing to inefficient use of electric energy. Recently, many promising power factor correction (PFC) techniques have been proposed for rectifiers. Apart from application of active and passive filters, the best solution is in using pulse width modulated (PWM) rectifiers. Research interest in three-phase PWM rectifiers has grown rapidly over the last few years due to some of their important advantages, such as power regeneration capabilities, control of dc-bus voltage over a wide range, and low harmonic distortion of input currents.

Since the converter has abilities to control the input currents in sinusoidal waveforms, unity power factor [1]operation can be easily performed by regulating the currents in phase with the power-source voltages. From the control point of view, power electronic circuits and system constitute excellent examples of hybrid systems, since the discrete switch positions are associated with different modes of continuous time dynamics

Lyapunov theory has for long time been an important tool in linear as well as nonlinear control. However, its use within the nonlinear control has been changed by the difficulties to find the Lyapunov function for a given system. If one can be found, the system is known to be stable, but the task of finding such function has often been left to the imagination and experience of the designer [6].

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A. Aims and Objectives

The aims of this paper includes the design of the control law of the boost rectifier to determine the occurrence of control input function in both ac current and dc voltage control of the converter, to achieve the control of power and grid current in steady state and transient operating conditions and to implement Discrete event based switching control strategy with respect to lyapunov stability theorem for the switching action of three phase converter

The objectives are to limit the Total Harmonic Distortion (THD) of the input ac voltage and current and to control and to improve the Power Factor

II. ANALYSIS OF THREE PHASE CONVERTER

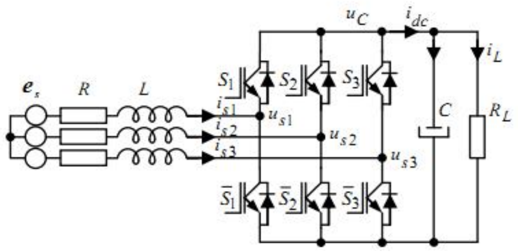

Fig. 1 Three Phase Converter

The circuit diagram of three phase converter is shown in Fig 1.The main circuit consists of a bridge rectifier made up of six power transistors with antiparallel diodes, which is connected to the three-phase supply, through an inductor *L*. A load and a capacitor *C* are connected to the dc side of the converter. The inductor *L* performs the voltage boost operation in combination with the capacitor *C* and at the same time acts as a low pass filter for the ac line current.

The dynamics of a three-phase boost rectifier in the three-phase reference frame for ac current control system is described as:

$$L\frac{di_j}{dt} + Ri_j = e_{sj} - u_{sj}$$

$$u_{sj} = \left\{ d_j - \left\{ \frac{(d_1 + d_2 + d_3)}{3} \right\} u_c \right\}, j = 1,2,3... \quad (1)$$

and for output voltage control system as:

$$C\frac{du_c}{dt} = i_{dc} - i_L = i_1 d_1 + i_2 d_2 + i_3 d_3 - \frac{u_c}{R_L} \quad (2)$$

where d_j is the duty ratio

From the point of view of the commutation process, converters can be classified in two important categories:

- Line Commutated Controlled Rectifiers (Thyristor Rectifiers)
- Force Commutated PWM Rectifiers.

Force-commutated rectifiers are built with semiconductors with gate-turn-off capability and it allows the commutation of the valves hundreds of times in one period, which is not possible with line commutated rectifiers, where thyristors are switched ON and OFF only once a cycle. This feature has the following advantages: a) the current or voltage can be modulated (Pulse Width Modulation or PWM), generating less harmonic contamination;b) power factor can be controlled, and even it can be made leading.

There are two ways to implement force-commutated three-phase rectifiers: a) as a current source rectifier, where power reversal is by dc voltage reversal; and b) as a voltage source rectifier, where power reversal is by current reversal at the dc link. The PWM pattern controls the rectifier in two different ways: 1) as a voltage source current controlled PWM rectifier, or 2) as a voltage source voltage controlled PWM rectifier. The first method controls the input current, and the second controls the magnitude and phase of the voltage. The current controlled method[2] is simpler and more stable than the voltage-controlled method. The current control is achieved by measuring the instantaneous phase currents and forcing them to follow a sinusoidal current reference. Input voltages and currents should be sinusoidal shaped without a phase delay between the voltage and the current and output dc voltage should be a constant value by change of voltage dependent current and parameters of the converter [4]

III. SVPWM Based Switching COntrol

Space-vector pulse width modulation (SVPWM) technique has become a popular PWM technique for three-phase voltage-source converters. The structure of a typical three-phase converter is shown in Fig 1. The u_{s1}, u_{s2}, u_{s3} are the output voltages of the converter.

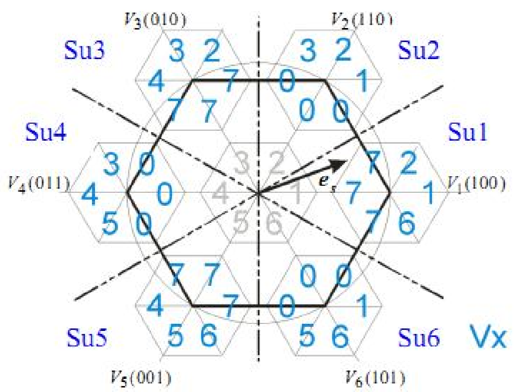

Fig. 2 The Basic Space Vectors (Normalized w.r.t. e_s) and Switching States

The six power transistors that shape the output are controlled by S_1, $\sim S_1$, S_2 , $\sim S_2$, S_3 and $\sim S_3$. [5]When an upper transistor is switched on (i.e., when S_1, S_2 or S_3 is 1), the corresponding lower transistor is switched off (i.e., the corresponding $\sim S_1$, $\sim S_2$ or $\sim S_3$ is 0). The on and off states of the upper transistors, or equivalently, the state of S_1, S_2 and S_3 , are sufficient to evaluate the output voltage for the purpose of this discussion. As shown in Fig 2, there are eight possible combinations of on and off states for the three upper power transistors

TABLE I. Sign E_s Vs Sign D_j

Sign E_s		Su 1	Su 2	Su 3	S u4	S u5	S u6
Sign D_j		10 0	11 0	01 0	0 11	0 01	1 01
S di0	0 00	V 7	V 0	V 7	V 0	V 7	V 0
S di1	1 00	V 1	V 1	V 7	V 0	V 7	V 1
S di2	1 10	V 2	V 2	V 2	V 0	V 7	V 0
S di3	0 10	V 7	V 3	V 3	V 4	V 7	V 0
S di4	0 11	V 7	V 0	V 4	V 5	V 4	V 0
S di5	0 01	V 7	V 0	V 7	V 6	V 5	V 5
S di6	1 01	V 6	V 0	V 7	V 0	V 6	V 6
S di7	1 11	V 7	V 0	V 7	V 0	V 7	V 0

The proposed logical event-driven grid current control[3] can be realized in the form described in Table I, where states of grid current control error are presented by *sign(Dj)* (*Dj* $=S_1$, $S_2.S_3$) and currently active voltage sector is presented by *sign Es* (e_{S1}, e_{S2}, e_{S3}). The transition between converter switch states is performed by switching only one converter leg, converter switching frequency grid current chattering are reduced.

IV. Proposed Control Scheme

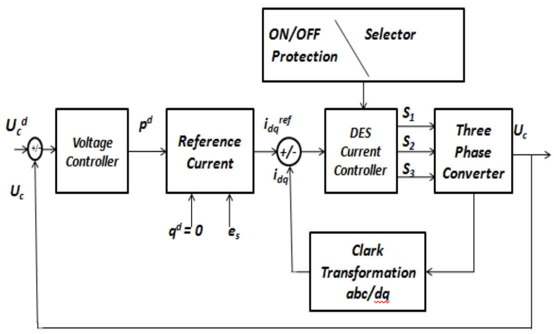

Fig. 3 Block Diagram of Proposed method

Fig. 3 shows the block diagram of proposed method. The description about the control method is discussed in the following sections.

A. Output Voltage Control

The unity power factor of ac/dc boost rectifier will be achieved for $u_C = u_d$, $u_q = 0$ in d-q output reference frame.

The output voltage control error

$$\sigma_u = u_c^d - u_c \tag{3}$$

determines the input dc current i_{dc} which also plays the role of the rectifier output current.

With $\frac{d}{dt}(\sigma_u) = -d_u \sigma_u$ we get a robust PI-control algorithm [8]:

$$i_{dc}(k) = i_{dc}(k-1) + \left(\frac{G_u C}{T}\right) * \left((1 + Td_u)\sigma_u(k) - \sigma_u(k-1)\right) \tag{4}$$

In the proposed algorithm the output load resistance R_L does not appear, therefore the control is independent of its value. The resistive load can change its value in transient states, i.e. which includes step change of its value. The rectifier dc current i_{dc} ,which forms an input for dc boost rectifier part is influenced by a dc output voltage error $\sigma_u(k)$, dc bus capacitor C, used sampling time T and feedback gain G_u. The asymptotical stability of algorithm is guaranteed with the proper choice of parameter du.

B. Reference Input Power

The reference input active power would be determined with dc current i_{dc} and bus voltage u_{dc}:

$$p^d = u_{dc} i_{dc} \tag{5}$$

C. Unity Power Factor Control

The calculation of active and reactive components of modulating currents is produced by the method of instantaneous power, known as the “Akagi-Nabae theory” [8]. This theory, also known as pq-theory, is based on Clark transformation. Thus, the reference current signals i_{sd}^{ref} , i_{sq}^{ref} can be received as:

$$\begin{bmatrix} i_{sd}^{ref} \\ i_{sq}^{ref} \end{bmatrix} = \frac{1}{e_{sd}^2 + e_{sq}^2} \begin{bmatrix} e_{sd} & e_{sq} \\ e_{sq} & -e_{sd} \end{bmatrix} \begin{bmatrix} p^d \\ q^d \end{bmatrix} \tag{6}$$

where p^d and q^d are reference active and reactive power signals.

Reference current signals in three-phase system are calculated by reverse Clark transformation. For unity power factor $q^d = 0$ and the reference grid current will

$$i_{sd}^{ref} = \left(\frac{e_{sd}}{\left(e_{sd}^2 + e_{sq}^2\right)}\right) * p^d \tag{7}$$

$$i_{sq}^{ref} = \left(\frac{e_{sq}}{\left(e_{sd}^2 + e_{sq}^2\right)}\right) * p^d \tag{8}$$

One of the main advantages of pq-theory is that there is no need for phase synchronization with system voltages. Also, average components p and q can be easily detected (filtered) by means of low-order low-pass filters. The latter makes positive impact on system dynamic and stability.

D. Lyapunov Theorem Based Control Method

1) Lyapunov's second method for stability

Lyapunov, proposed two methods for demonstrating stability. The first method developed the solution in a series which was then proved convergent within limits. The second method, which is almost universally used nowadays, makes use of a *Lyapunov function V(x)* which has an analogy to the potential function of classical dynamics. It is introduced as follows. Consider a function $V(x) : Rn \rightarrow R$ such that

- $V(x) \geq 0$ with equality if and only if $x = 0$ (positive definite)
- $\frac{d}{dt} V(x) \leq 0$ with equality if and only if $x = 0$ (negative definite).

Then V(x) is called a Lyapunov Function candidate and the system is asymptotically stable in the sense of Lyapunov .

2) Design of Control Law For Three Phase Converter

The aim of this project is the design of a control law for a boost rectifier in order to achieve a output voltage and grid current control in a steady state and transient operation conditions. The feedback system is globally asymptotically stable in the sense of Lyapunov stability theory. Therefore, we are interested in the aim extension of the Lyapunov function concepts.

On the basis of Lyapunov stability theory, a positive definite scalar function V, as a candidate for the Lyapunov function, is to be found, such that the total energy of the system is continuously dissipated. In such a case, any nonlinear system must eventually settle down to an equilibrium point. For the Lyapunov function candidate

$$V = \frac{1}{2}\Delta i_s^T \Delta i_s = \frac{1}{2}\left(i_s - i_s^d\right)^T \left(i_s - i_s^d\right) \tag{9}$$

the stability requirement will be fulfilled if control can be selected as such, that the derivative of the Lyapunov function candidate is negative.

Derivatives of the current control error (9) may be expressed with the voltage equation

$$\frac{d}{dt}\left(i_s - i_s^d\right) = \frac{1}{L}\left(e_s - Ri_s - u_s(V_i)\right) - \frac{d}{dt} i_s^d \tag{10}$$

where i_s^d , i_s are desired and actual grid current,

$u_s(V_i)$ is voltage control input,

Ri_s is resistive voltage drop and

e_s is ac input voltage.

For $d(\Delta i_s)/dt = 0$ the equivalent control voltage [7] can be expressed as:

$$u_{equ} = e_s - Ri_s - L\frac{d}{dt} i_s^d \tag{11}$$

and derivative of Lyapunov function is

$$\frac{d}{dt}V(x) = \left(i_s - i_s^d\right)\frac{\left(u_{equ} - u_s(V_i)\right)}{L} < 0 \qquad (12)$$

The conditions for the sequential switching of the power converter are selected as:

$$S_1 = \frac{1}{2}(1\text{-sign}(A))$$

$$S_2 = \frac{1}{2}(1\text{-sign}(B))$$

$$S_3 = \frac{1}{2}(1\text{-sign}(C))$$

where

$$A = \left(i_{sd} - i_{sd}^{ref}\right)$$

$$B = -\frac{1}{2}\left(i_{sd} - i_{sd}^{ref}\right) - \frac{\sqrt{3}}{2}\left(i_{sq} - i_{sq}^{ref}\right)$$

$$C = -\frac{1}{2}\left(i_{sd} - i_{sd}^{ref}\right) + \frac{\sqrt{3}}{2}\left(i_{sq} - i_{sq}^{ref}\right) \qquad (13)$$

which is evolved from the Lyapunov function derivative. When U_{dc} has enough magnitude that $V<=0$, than $V \rightarrow 0$ and $i_s \rightarrow i_s^d$.

V. IMPLEMENTATION

A. Steps To Implement Discrete Event Model

- Obtaining feedback signals such as input ac current, input ac voltage, output dc current, output dc voltage to generate current error signals
- Generating input voltage sector states
- Implementing the table obtained for current error signals and voltage sector states using Hybrid controller

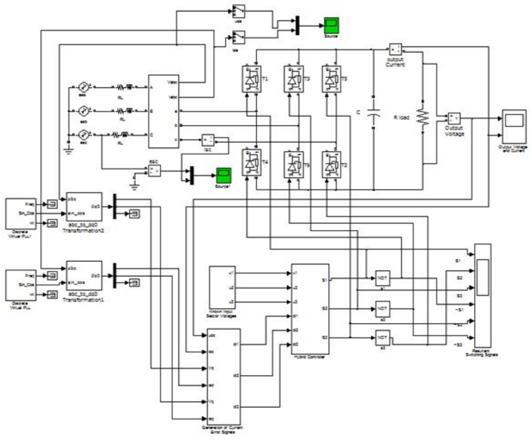

Fig .4 Simulink model of proposed method

The simulink model shown in Fig 4 has three voltage sources phase shifted by 120˚ in order to obtain the three phase voltage input to the converter. The resistance and inductance are connected serially to the three phases of the voltage source.Three phase voltage and current in abc axis is transformed to dqo axis using abc to dqo transformation block in simulink. The o axis signal is blocked using the terminator. The available voltage and current signals in dq axis is given as the feedback signals to generate current error.

Three phase converter is composed of six thyristor switches, where three switches are connected to the top of the three phase leg and other three to the bottom of the leg. The gate pulses to the switches are given from the output of the hybrid controller. As no two switches in the same leg can be switched on at the same instant, the switching pulses to the upper and lower switches in a leg are inverted. The resistive load is connected at the output side of the three phase converter. The filter capacitor is connected in parallel to the resistive load to remove the noise in the circuit. The harmonics is analysed for three phase input current and voltage after developing the discrete event model using FFT analysis.

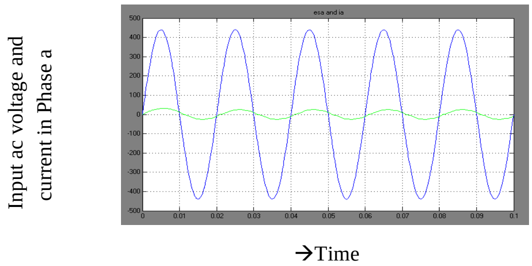

Figure 5(a) Input ac voltage and current in Phase a Vs Time

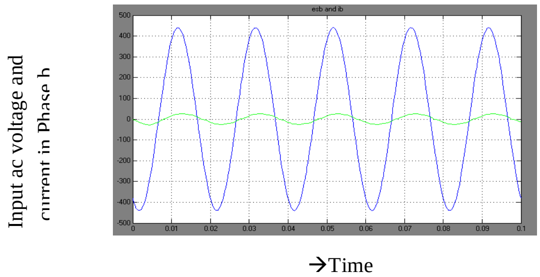

Figure 5(b) Input ac voltage and current in Phase b Vs Time

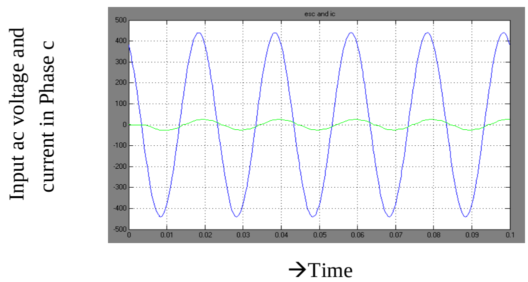

Figure (c) Input ac voltage and current in Phase c Vs Time

The ac current in the three phases of the converter after implementing the discrete event model is analyzed and shown in Fig 5(a),(b),(c).The input ac voltage and current are in phase in all the three phases a,b,c. Thus the unity power factor is achieved in the three phase converter using discrete event model. The FFT analysis for harmonics is shown in Fig 6.

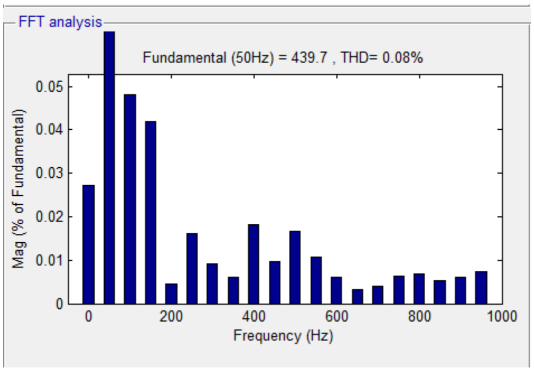

Fig 6 FFT Analysis for three phase input current using Discrete event model

VI. Conclusion

The hybrid based discrete event model is designed for auxiliary steering and protection functions for a three phase rectifier. The proposed discrete event model generates switching signals and controls the switches of the three phase converter. The power factor is improved by neglecting the reactive power and controlling only the active power. The stability is taken into account for analyzing the voltage and current using Lyapunov method. The feedback system is globally asymptotically stable in the sense of Lyapunov.

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