Study and Simulation of Current Controlled PWM Inverters and their applications

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Abstract— A voltage source inverter can be operated as a voltage source or current source depending on the modulation technique used. Traditional modulation techniques for the control of Voltage Source Inverters (VSI) generally use open loop switching wherein the inverter produces a set of voltages with specified fundamental magnitude and phase. These techniques thus operate the VSI as a voltage source. There are many applications such as active power filters, grid connected inverters and vector controlled AC drives wherein the VSI must be operated in a closed loop fashion. The inverter tracks a reference current and is thus operated as a current source for achieving high performance in terms of controllability and dynamic response.

Keywords- Hysteresis, Current Controlled PWM, VSI, Closed loop switching

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I. INTRODUCTION

Voltage source inverters have traditionally been operated as voltage sources where the controller generates gate pulses for obtaining an output voltage with a particular fundamental magnitude and frequency. In the case of traditional modulation techniques like Sinusoidal Pulse Width Modulation (SPWM), the switching is completely independent of the actual line current flowing through the inverter. The conventional methods have been discussed in detail in [1].These are thus essentially open loop systems where the switching patterns are predetermined. There is no feedback and thus the system cannot ensure whether the output voltages and currents remain within desired margins. Current in this case and the nature of current (both magnitude and phase) will be dependent on the connected load. The VSI in these cases is being operated as a voltage source. With modern inverter technology such as in high performance vector controlled AC drive systems [2], the VSI as a voltage source does not provide the level of performance which can be achieved by operation of the VSI as a current source. For controlling the exact phase relationship between the stator and rotor fluxes current source techniques are utilized that tend to drive the motor to whatever voltage required to obtain the desired stator current. In this system, the controller generates the reference stator current waveform for maximum performance and the inverter must force this current through the stator windings. This allows excellent motor control in terms of speed as well as torque. Current Controlled Voltage Source Inverters are used in many low and medium voltage utility applications when the inverter line current is required to track a particular reference within a specified error margin.Some of the major applications include Active Power Filters (APF), Gird connected inverters and Vector Controlled AC Induction Motor(ACIM), Permanent Magnet Synchronous Motor (PMSM) and Brushless DC Motor(BLDC) Drives. The switching pattern of current controlled PWM (CC-PWM) inverters is produced through line current feedback and it is not predetermined.

The basic control structure of all the above mentioned applications aresimilar in the sense that it consists measurement of the line currents (and voltages if required), computation of reference currents using application specific algorithms and the final component is the current controlled PWM inverter which tries to minimize the error between the reference currents and the actual currents flowing through the lines.

Hysteresis control and PI control are two of the widely used methods for current control and have been discussed in this paper. The advantages and drawbacks of each with respect to the other have also been listed.

II. INVERTER MODEL

We consider the system structure of a single phase grid-connected inverter [3] which includes a few parts: the dc bus voltage V_{dc}, the dc bus capacitance C_d, the full bridge inverter composed by four IGBTs, filtering inductance L, loads, and power grid voltage u_s. It is shown in Figure 1. It is simply the basic H-Bridge and is the most commonly used Inverter structure. It is an extremely versatile structure which can be used for generating various kinds of outputs. The control signals (which depend on the modulation technique used) will decide whether the fundamental output voltage is a square wave, a sine wave or any random wave as required by the application.

We drive the inverter using control signals generated by current controlled PWM technique and thus obtain the desired current waveform as the inverter output.

The controller provides the appropriate gate pulses to the switches to ensure that the error between the reference current and the actual load current is minimized. When T1 and T4 are on, the voltage across the load is $+V_{dc}$ and so the current increases. Similarly, when T2 and T3 are on, the voltage across the load is $-V_{dc}$ and the current decreases.

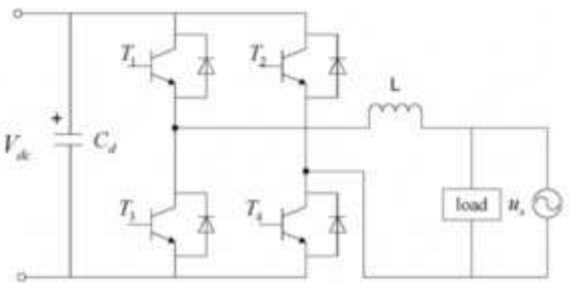

Figure 1: Structure of Grid Connected Inverter

III. CURRENT CONTROLLED PWM

In current controlled PWM, load currents are measured and compared with reference currents. The errors are used as inputs to the PWM modulator, which provides inverter switching signals. The main objective of current controller is to force the load current vector according to the reference current trajectory. Two of the commonly used methods for achieving this are Hysteresis control and PI control.

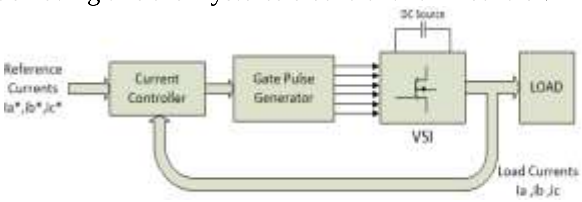

Figure 2: Functional Block diagram of Current Controlled PWM Inverter

Figure 2 shows the functional block diagram of a current controlled PWM inverter. As is shown in the figure, it is a closed loop system where the switching pulses are dependent on the load currents. The load currents are fed back to the controller which constantly compares them to the reference currents. The error generated is processed by the controller whose output is used by the gate pulse generator to give the switching pattern of the inverter switches so as to minimize the error.This kind of a current control loop is present in most of the modern vector drives, Active power filters and grid connected inverters. It can be used in any application which requires a controlled current source.

IV. TECHNIQUES OF CURRENT CONTROL IN VOLTAGE SOURCE INVERTERS

A. Hysteresis Current Control:

Among all current control techniques, the hysteresis controller is widely used because of its simplicity of implementation and fast response current loop [5]. It is fast, simple, stable and does not require any carrier. The main disadvantage is the variable switching frequency.

The load current is constantly compared to the reference current and the error is not allowed to exceed the Upper and Lower limits. For S1 and S3 on and S2 and S4 off, $+V_{dc}$ is applied across the load. Thus the current rises. Similarly, for S1 and S3 off and S2 and S4 on, $-V_{dc}$ is applied across the load and current falls. This will be true for both positive and negative currents, i.e. if the current is negative and S2 and S4 are on, it will fall, meaning its magnitude will increase in the negative direction.

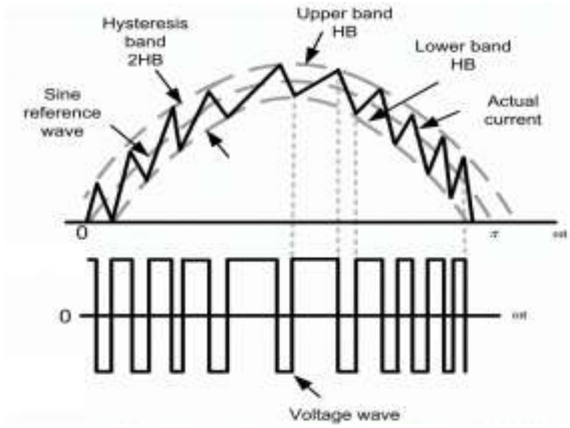

Figure 3: Hysteresis Current Control

Thus the inverter has only two states of $+V_{dc}$ and $-V_{dc}$ and by switching between the two according to the current error, the inverter current can be made to lie within the hysteresis band as shown in Figure 3.

The rate of current rise and fall depends on the load inductance and magnitude of V_{dc}. Also from the figure, we can see that faster the rise and fall of current, smaller will be the times required for current to go out of the hysteresis boundaries and higher will be the switching frequency. We also see that the switching frequency will increase as we reduce the current error tolerances, i.e. the hysteresis bandwidth. Power electronic switches have a maximum switching frequency rating. If operated at switching frequencies higher than this rating, they may get damaged due to overheating caused by the increased switching losses.

While a high switching frequency allows us to have narrower hysteresis bandwidth and thus tighter control over the current, it increases the cost of the switches as well as their cooling. Hence, a realistic and feasible switching frequency is selected during the designing of the hysteresis controller by taking into account the allowable current error, load inductance and voltage of the DC bus, V_{dc}.

B. PI Current Control:

In PI (Proportional plus Integral) control, the load current is compared to the reference current and the respective error is generated. This error then gets processed by a PI controller. The main characteristic of PI is that it minimizes steady state error. A PD (Proportional plus Derivative) controller on the other hand improves the speed or dynamic response of the system, that is the rise times and settling times. A PID (Proportional plus Integral plus Derivative) is a combination of the two and offers the benefits of both but a PD or PID controller but is almost never used for inverter control as the derivative term may lead to system instability. The output of the PI controller is analog and must be converted into gate pulses so that it can be applied to the switches. This is done using simple pulse width modulation method by comparing it to a high frequency carrier wave.

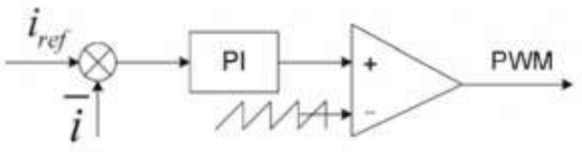

Figure 4: PI Current Control

A simple schematic of the system is shown in Figure 4. Thus analog output of the PI controller gets converted into duty cycle of the PWM signal. Thus we see that the switching frequency will remain constant in case of PI control and is equal to the frequency of the carrier wave. In this method, the switching is thus synchronous, i.e. at fixed intervals of time, whereas in case of hysteresis control, it is asynchronous and switching occurs whenever the current will go out of the error limits.

While the variable switching frequency and asynchronous operation are a disadvantage of hysteresis control [7], they are the very reason for the excellent dynamic response offered by this method. Variable switching frequency has two major disadvantages: a) It becomes extremely difficult to design a filter at the output to remove the switching frequency components. b) The inverter produces a lot of audible noise at varying frequencies and levels.

PI control is generally suitable for implementation on modern microcontroller and DSP chips as these contain various PWM modules and the duty cycle calculated by the PI controller is simply written into the duty cycle register of the microcontroller. Hysteresis control, on the other hand is very difficult to implement digitally on microcontrollers and DSPs due to its asynchronous nature. Thus it is generally a practice to implement hysteresis controllers using analogcircuits. In most applications, the reference currents are calculated by the DSP, whereas the current control is carried out by externally connected hysteresis control circuits.

A majordisadvantage of PI control over Hysteresis control is the need for a fairly accurate mathematical model in the case of PI control. PI controller must be tuned properly for stable operation which is not the case for hysteresis control which is inherently stable as mentioned earlier.

Hence one must consider all these advantages and drawbacks of the two methods and choose one according to the application.

Irrespective of the method being used (Hysteresis, PI, or any other), it is obvious that for achieving current control, the load must have an inductive component ensuring finite current rise and fall rates. This is because the power electronic switches can only be operated in saturation or cut off and so either positive or negative V_{dc} gets applied across the load.This causes the current to rise or fall respectively. For a purely resistive load, the current will also only take values of positive or negative maximum. There are more voltage levels in case of multilevel inverters but the number of voltage levels will always be finite. While multilevel inverters can provide better controllability overall (current as well as fundamental voltage), it still needs the load to be inductive.

V. APPLICATIONS OF CC-PWM

A. AC Vector Control Drives:

The vector control motor drives, consists of two control loops. The outer speed control loop compares the motor speed to the reference speed and the error is used by the controller to generate the reference stator currents which will minimize this error. These reference currents are fed to the inner current control loop which is similar to the one shown in figure 2. It forces the stator current vector to follow the reference current vector. Thus the desired rotor and stator fields are produced and they can be maintained perpendicular to each other to achieve maximum torque as is the case of a DC motor. There are various vector control algorithms being used in modern ac drives such as Field Oriented Control (FOC), Direct Torque Control (DTC) etc. While FOC generally uses PI current controller, DTC uses Hysteresis current controllers. Nowadays, scalar control of Induction Motors (constant V/f method) is being replaced by vector control due to its superior dynamic performance and controllability.

B. Active Power Filter:

In Active power filters, the aim is to make the source currents purely sinusoidal and in phase with the source voltages. In a normal power system, the supply is a constant voltage source and so the current drawn (magnitude, phase as well as nature) will be completely dependent on the load characteristics. The load is nonlinear and thus draws several harmonics depending on its characteristics. The load power can be resolved into three components: active, reactive and harmonic. The component of current which supplies the active power is obviously sinusoidal and in phase with the supply. The basic concept of active power filtering is to supply the reactive and harmonic components of the currents using a VSI and so the remaining current, that is the active component will be supplied by the source. The major challenge in achieving this is to calculate the reactive and harmonic components of the load current so that their sum can be provided to the inverter as the current reference. There are different methods for doing this, the most popular being instantaneous pq theory and dq theory. Once calculated, these references are provided to the current control loop and the inverter injects these currents into the system (with minimum possible error) so as to make the current being drawn from the source purely sinusoidal.

C. Grid Connected Inverters:

Distributed generation (DG) systems generally produce dc or variable ac output. They rely on current controlled PWM inverters for synchronization with the utility grid. The main objectives of the inverter is to 1)maintain grid stability 2)active and reactive power control through voltage and frequency control 3)Power Quality improvement, i.e. reduction of harmonics injected into the system. A Phase locked loop is used to lock the grid and inverter frequency and the current controller maintains the current vector according to the reference for control of active and reactive power flow between the grid and (DG).

VI. SIMULATION RESULTS

This section gives the details of the simulation carried out. The system shown in figure 5 is simulated in MATLAB Simulink. It consists of a DC source, an H-Bridge single phase inverter and an RL load. The current through the RL load is to be controlled at desired reference value. The current should be independent of the load which is verified by changing values of R.

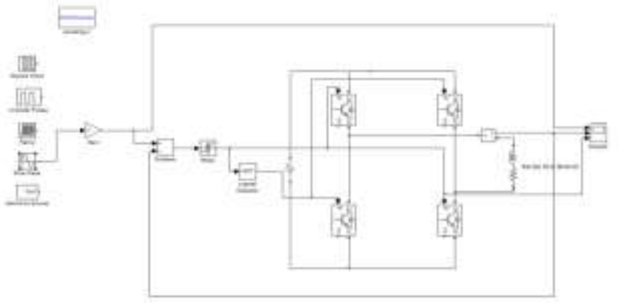

Figure 5: Simulation Model

The power circuit is thus the same as any common single phase inverter but due to the use of current controlled PWM, it acts like a current source as opposed to a voltage source. The switching patterns are generated by a hysteresis controller. The reference currents are fed to the hysteresis controller and the switching patterns generated keep the actual load current within the hysteresis band which was taken as 0.8A in all cases. The system was tested for different reference inputs. The simulation parameters are given in Table 1.

For a voltage source, the output voltage is fixed and the load current varies according to the characteristics of the load. But as a current source, the current remains constant (or varies according to the reference trajectory) and remains independent of the load. This is verified in the simulation by varying R from 2ohms to 10ohms. It is observed that the output current waveform is almost same in both the cases. The performance of the system was assessed by whether it can successfully track all the inputs provided to it as reference signals and the response time and error at the output. The details of the various test signals used as reference inputs are provided in table 2.

TABLE I. SIMULATION PARAMETERS

Parameters	**Values**
DC Voltage (Vdc)	400V
Load Resistance (R)	2Ω
Load Inductance (L)	10mH
Hysteresis Band (δ)	0.8A

TABLE II. REFERENCE INPUTS

Signal	**Details**
Square Wave	14A peak to peak, frequency 50Hz
Square Pulses	6A Amplitude, 50% duty ratio, 50Hz (Unipolar)
Ramp	7A Amplitude, 50Hz (Unipolar)
Sinusoidal	18A Peak to Peak, 50Hz
Random Wave	-

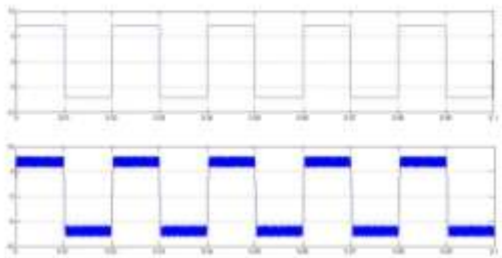

Figure 6(a): Response to Square Wave

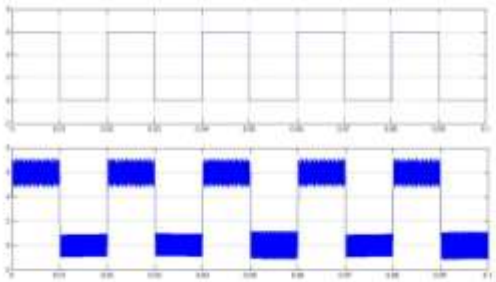

Figure 6(b): Response to Square Pulses

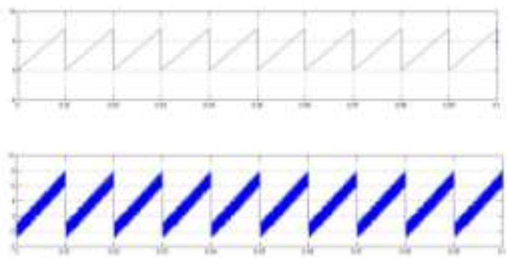

Figure 6(c): Response to Ramp wave

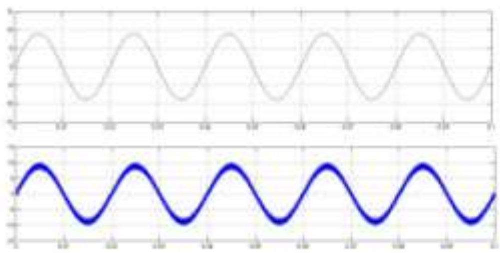

Figure 6 (d): Response to Sine wave

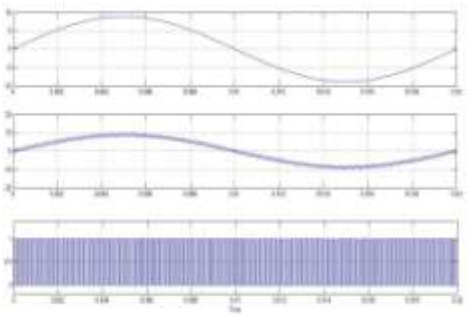

Figure 6 (e): Response to Sine wave Single Cycle

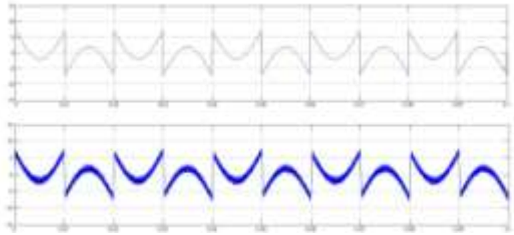

Figure 6 (f): Response to Random wave

VII. CONCLUSION

This paper presented the operation of Voltage Source inverter as a controlled current source. The Hysteresis and PI current control methods were studied. Applications which require the current controlled PWM inverter were studied. The Hysteresis current controller was simulated in MATLAB Simulink and its performance was studied under a variety of test signals. It could successfully track all the reference current inputs. The hysteresis current control method is found to be simple, fast and stable. The dynamic response was good and the system was stable in all the cases.

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