

Research Article

Adaptive Modified Hysteresis Current Control for Reduction of Switching Losses in Grid Connected Solar Inverters

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Abstract: Current Control logic plays an important role in the performance of Grid connected inverters. In the present work Adaptive Modified Hysteresis controller has been used for generation of switching pulses to the minimally switched grid connected inverter. Different from the previous works the new control logic helps in maintaining the instantaneous switching frequency low and nearly constant with reduction of switching losses to one-third of that of the conventional type. Considerable reduction in Total harmonic distortion of supply current, better DC bus voltage stabilization, good reactive power compensation, satisfactory performance under unbalanced source and load conditions and good dynamic response is also achieved. The experimental verification is done using SIMULINK/REALTIME WINDOWS TARGET. Present control logic is compared with conventional hysteresis controller with and without adaptive control to prove the effectiveness.

Keywords: Adaptive current control, modified hysteresis controller, reactive power compensation, switching frequency, switching losses, total harmonic distortion

INTRODUCTION

Search for pollution free energy source has led to the development of renewable energy systems. Among the renewable energy sources solar energy is abundant and inexhaustible. DC power from Photo Voltaic (PV) arrays is boosted using DC-DC converters and further converted to AC using inverters before connecting to the grid (Belaidi *et al.*, 2012; Paal *et al.*, 2011; Hossain *et al.*, 2012) three phase grid connected voltage source inverters interface PV systems with grid. Maximum Power Point Tracking (Hamrouni *et al.*, 2008; Tsang and Chan, 2013; Nabil *et al.*, 2011), proper control of power injected into the grid, low harmonic distortion of currents injected into the grid and high power factor are some of the requirements of grid connected inverters.

In the present scenario of energy crisis many studies are being done on feasibility using grid connected inverters fed from Photo voltaic arrays, fuel cells etc with active filter functions (Reza and Gevorg, 2013; Ilango *et al.*, 2012) Quality of photo voltaic power depends on output current of the inverter. This necessitates efficient Current control of Grid Connected inverters (Hamrouni *et al.*, 2008).

Several current control techniques has been reported in literature for generation of gating pulses to the solid state switching devices of three phase grid connected inverter. This include Hysteresis control (Naimish and Ajitsinh, 2012), Sliding mode control (Teshfahunegn *et al.*, 2009), Adaptive control (Murat

and Engin, 2005), Fuzzy logic control (Jayachandran *et al.*, 2013), Modified Hysteresis control (Nandakumar and Aseem, 2011) etc.

Wide acceptance of Hysteresis band current control method owe to quick current controllability, ease of implementation, fast response and inherent peak current limiting capability. No information about system parameters is needed for this. But variable switching frequency and high switching losses owing to control of all the six switches of the inverter are the major drawbacks of conventional hysteresis controller. Increased inverter operating frequency helps in obtaining better compensating current waveform, but results in increased switching losses.

In modified hysteresis controller only 2 switches are controlled at high frequency at any instant of time (Nandakumar and Aseem, 2011). This reduces the switching losses to one third of that of conventional controller where all the six switches are to be controlled. Even though the use of Modified Hysteresis controller results in reducing the switching losses to one-third, it is insufficient to maintain current THD within the specified limits. To overcome this, pulses to the Modified hysteresis controller is generated employing Adaptive control by modifying pulses from the conventional hysteresis controller. Problem of variable switching frequency with Modified hysteresis controller is also sought out with adaptive control.

In the present study active filter function of a grid connected inverter is dealt in detail to explain Adaptive

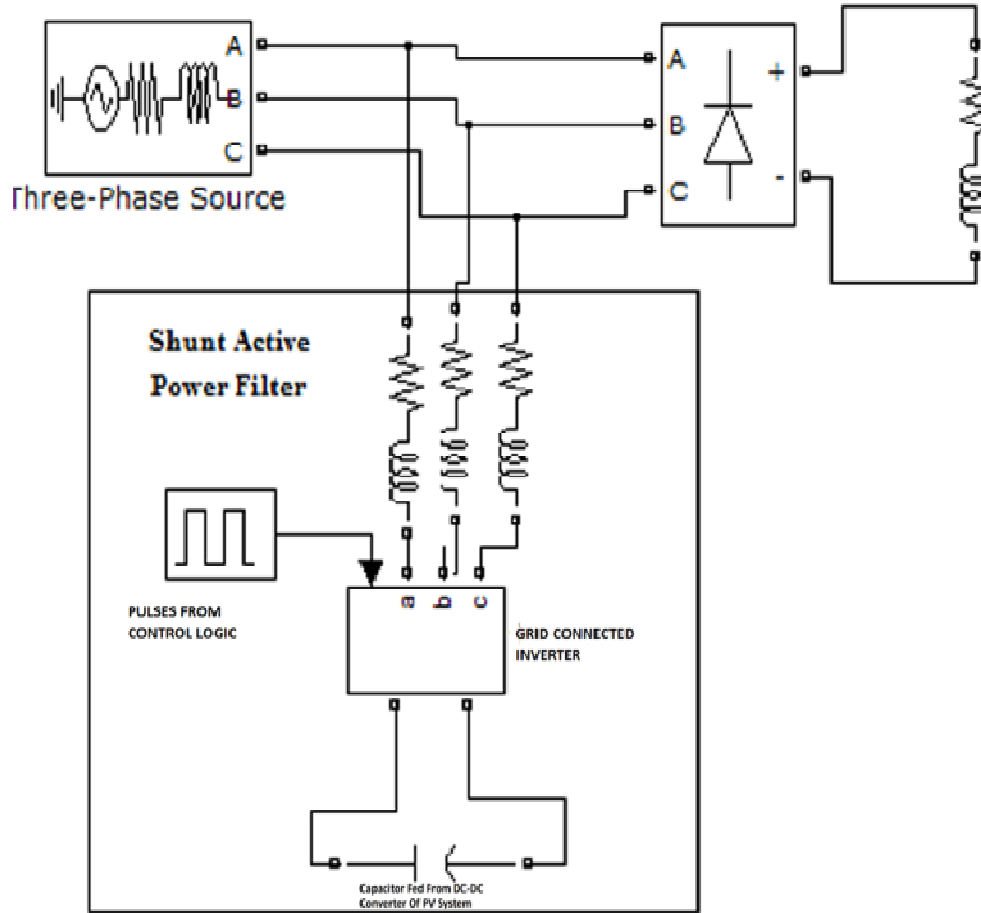


Fig. 1: Configuration of shunt active power filter

modified Hysteresis current Control. Output Voltage from the solar array is boosted and fixed at 300 volts. Instantaneous switching frequency is optimized, reduced and maintained nearly constant and THD is brought within the limits specified by the standards using Adaptive control. Reduced instantaneous switching frequency obtained through Adaptive control reduces the switching losses further. Better DC bus voltage stabilization is also achieved.

METHODOLOGY

System configuration: Voltage source inverter based three phase grid connected inverter with control circuit is discussed in this study. It acts as a shunt active power filter and is connected in parallel with the harmonic producing loads at the Point of Common Coupling (PCC). Configuration of shunt active power filter is shown in Fig. 1 Shunt active power filter generates a current equal and opposite to that of harmonic current drawn by the load and injects it at the point of common coupling, making the source current sinusoidal. Desired current waveform or actual filter current is obtained by controlling the switching of Insulated Gate Bipolar Transistor (IGBT) switches in the inverter. Control of

wave shape is limited by switching frequency of inverter and available driving voltage across interfacing inductance.

Reference current generation using real and reactive power algorithm: The p-q theory is valid for any three-phase circuit conditions and has the advantage of instantaneously separating zero-sequence components from positive and negative sequence components, which may be present in the instantaneous three-phase four-wire voltages and currents. Reference compensation current for phase a, phase b and phase c is evaluated using Inverse Clarke’s transformation using “Eq. (1)” (Belaidi *et al.*, 2012):

$$\begin{bmatrix} I_a(t)^* \\ I_b(t)^* \\ I_c(t)^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_\alpha(t)^* \\ I_\beta(t)^* \end{bmatrix} \quad (1)$$

Modified hysteresis controller with adaptive band: Conventional fixed hysteresis band technique is very simple, easy to implement with robust current control,

Table 1: Selection of controlled phases

Voltage sector	Ua	Ub	Uc	Controlled	Un-controlled
0°-60°	+ve	-ve	+ve	A, C	B
60°-120°	+ve	-ve	-ve	B, C	A
120°-180°	+ve	+ve	-ve	A, B	C
180°-240°	-ve	+ve	-ve	A, C	B
240°-300°	-ve	+ve	+ve	B, C	A
300°-360°	-ve	-ve	+ve	A, B	C

Table 2: Selection of controlled switches (240°-300°) region (t₅)

I _a	I _b	I _c	S _{ap}	S _{bp}	S _{cp}	S _{an}	S _{bn}	S _{cn}
-ve	+ve	+ve		C	C	On		
-ve	+ve	-ve		C		On		C
-ve	-ve	+ve			C	On	C	
+ve	+ve	-ve		C		Off		C
+ve	-ve	-ve				Off	C	C
+ve	-ve	+ve			C	Off	C	

has good stability, fast response and inherent ability to control peak current without need for any information about system parameters. But, this method suffers from variable switching frequency, heavy interference, harmonic content around switching side band and irregularity of the modulation pulse position. These drawbacks result in high current ripples and acoustic noise.

To overcome these undesirable drawbacks, this study presents an Adaptive Hysteresis band controlled Modified Hysteresis controller.

In a three wire system given in it is sufficient to control current in only two phases. For compensating harmonic current at source side, harmonic current has to be injected into the grid from the inverter. To inject harmonic current, a generalized switching algorithm is developed based on grid voltage and injected current polarities (Nandakumar and Aseem, 2011). Phases having same polarity of voltage is selected for control. This results in low rate of change of inductor current and easier control. From the selected phases, controlling switches are selected based on the current polarity. The action of the controlled bridge in each 60° duration of line cycle is explained based on the polarity of source voltage and injected current. Table 1 shows controlled and uncontrolled phases corresponding to different grid voltage regions. In 240°-300° region Ua is negative, Ub and Uc are positive. B and C are the controlled phases and A is the uncontrolled phase. From the selected phases, controlling switches are selected based on the current polarity. Table 2 shows controlled and uncontrolled switches corresponding to 240°-300° grid voltage region. Controlled and uncontrolled switches corresponding to 0°-60°, 60°-120°, 120°-180°, 180°-240° and 300°-360° were also tabulated. Use of Modified Hysteresis controller results in reducing the switching losses to one-third since only two switches are controlled at a time, but is insufficient to maintain current THD within the specified limits. It also suffers from the problem of variable switching frequency like the conventional controller.

To overcome this problem pulses to the Modified hysteresis controller is generated using adaptive control

by modifying pulses from the conventional hysteresis controller. The output signal from the modified hysteresis controller is used to activate the power switches of the grid connected inverter. The switching logic for an inverter leg is given below.

If $IL < (IL_{ref} - HB)$, the upper switch is off and lower switch is on for the same leg.

If $IL > (IL_{ref} + HB)$, the upper switch is on and lower switch is off for the same leg. IL_{ref} is the line reference current and IL is the actual filter current of the respective leg.

Variable hysteresis band is given by:

$$HB = \left\{ \frac{0.125 U_{DC}}{f_c L} \left[1 - \frac{4L^2}{U_{DC}^2} \left(\frac{U_s}{L} + m \right)^2 \right] \right\} \quad (2)$$

where, f_c is modulation frequency, $m = di_c^{ref}/dt$ is the slope of reference current wave. U_{DC} capacitor voltage of Voltage source inverter, L is the interface inductance, U_s is the voltage of respective phase. Figure 2 shows the implementation of Adaptive control.

Hysteresis band is modulated at different points of fundamental frequency cycle so that the switching pattern of inverter is controlled. The “Eq. (2)” defines the hysteresis band that depends on the system parameters. By substituting the switching frequency we can get the hysteresis band value. Adaptive hysteresis band method allows to operate at nearly constant frequency. Adaptive hysteresis band current controller changes the hysteresis band width according to slope of reference current to optimize switching frequency of inverter and THD of supply current.

Switching algorithm: Let t_1, t_2, t_3, t_4, t_5 and t_6 represent the regions 0°-60°, 60°-120°, 120°-180°, 180°-240°, 240°-300°, 300°-360° of the voltage sector respectively (Jayachandran *et al.*, 2013; Nandakumar and Aseem, 2011; Thekkath and Prabha, 2013). Switches of the grid connected inverter are $S_{ap}, S_{an}, S_{bp}, S_{bn}, S_{cp}$ and S_{cn} . Let symbols X_a, X_b, X_c represent the polarity of reference currents $I_a^{ref}, I_b^{ref}, I_c^{ref}$, respectively. Boolean expressions formulated for enabling signals to switches S_{cp} and S_{cn} in terms of $t_1, t_2, t_3, t_4, t_5, t_6$ and X_a, X_b, X_c are given below. C_p and C_n are the pulses from conventional hysteresis controller:

$$S_{cp}(c) = (t_1 + t_2 + t_4 + t_5)X_c \quad (3)$$

$$S_{cp}(on) = t_6.X_c \quad (4)$$

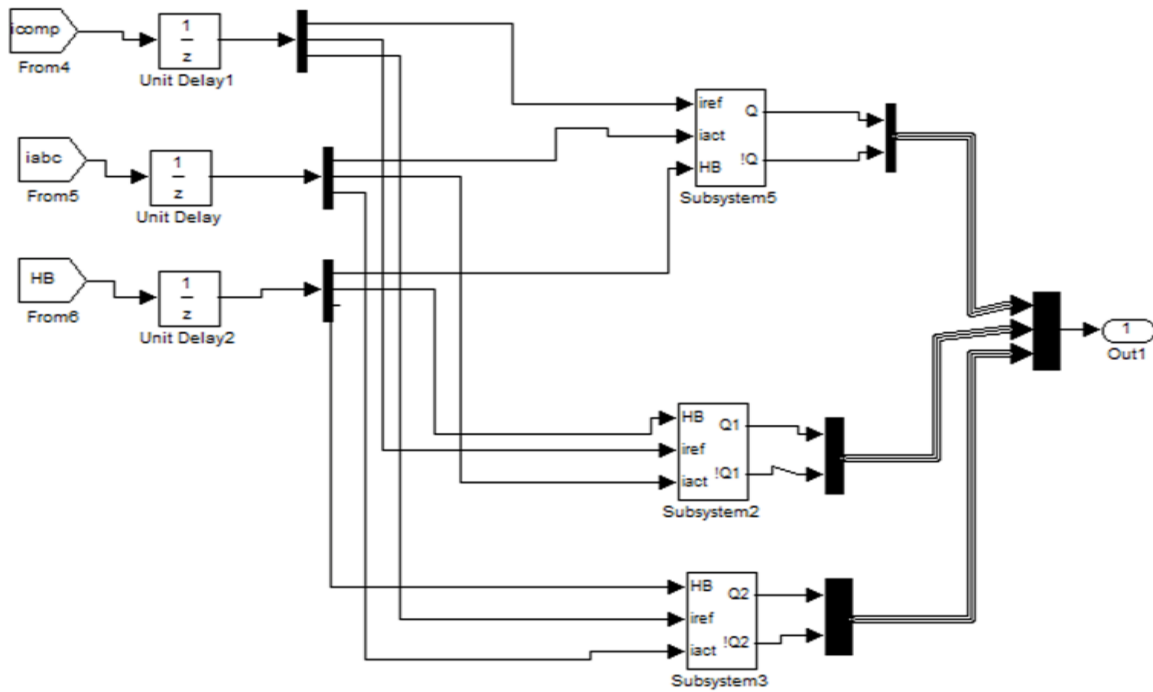


Fig. 2: Implementation of adaptive control

$$S_{cp} = S_{cp}(c) \cdot C_p + S_{cp}(on) \tag{5}$$

$$S_{cn}(c) = (t_1 + t_2 + t_4 + t_5) \cdot X'_c \tag{6}$$

$$S_{cn}(on) = t_3 \cdot X'_c \tag{7}$$

$$S_{cn} = S_{cn}(c) \cdot C_n + S_{cn}(on) \tag{8}$$

Similar expressions can be obtained for S_{ap} , S_{an} , S_{bp} and S_{bn} .

Synchronization: Phase Locked Loop (PLL) tracks the phase of measured voltages U_a , U_b and U_c . Proper operation under balanced and unbalanced voltage conditions is ensured by PLL. Voltage fluctuations at the dc-bus capacitor is used to calculate extra power loss in inverter. Corresponding phase current amplitude calculated using a Proportional-Integral (PI) controller, is multiplied with PLL output and is added to reference compensation current in each phase. The losses in shunt active power filter is thus taken care of by three phase source and dc bus capacitor voltage becomes a self supporting one.

Experimental verification using REALTIME implementation: REALTIME implementation of Adaptive Minimally Switched Grid connected Inverter was done using REALTIME WINDOWS TARGET

Table 3: Components used for REALTIME implementation

Source voltage	Three phase 180V L-L
Autotransformer	Three phase
Diode bridge rectifier	Three phase rectifier with power diodes 12FM 120
Resistive load	500 W
Voltage sensor	230/6V
Potentiometers	1 kΩ
Current sensor	HE0550T1
Regulated DC power supply	15V
Interfacing reactor	Variable up to 50 mH
Voltage source inverter	1200V, 75A
Data acquisition equipment	Advantech PCI1711

for experimental verification. The experimental set up includes a three phase source supplying a three phase diode bridge rectifier feeding a resistive load.

Advantech PCI-1711 was used for real time data acquisition. Efficient Computer performs the operation of control circuitry. Pulses from the Modified hysteresis controller with adaptive band width was taken as digital output through PCI-1711 card to trigger the voltage source inverter unit. Proper dead zone compensation was provided to ensure that switches of the same leg do not operate at the same time. Signals were captured and graphed in SIMULINK Scope blocks by using SIMULINK's external mode which enables us to observe the behaviour of the real-time system. Parameter tuning was done by editing SIMULINK blocks and changing the values of the parameters. Three phase voltage source inverter was connected back to supply through proper interface reactors. Components used for Real time implementation is shown Table 3.

EXPERIMENTAL RESULTS

Simulation was run in REALTIME. Figure 3 shows the THD of Uncompensated Source Current which is 29.03%. Figure 4 shows the hardware set up for real time implementation using REALTIME WINDOWS TARGET. Figure 5 shows the source current before and after compensation.

FFT analysis was done on compensated source current of Adaptive minimally switched grid connected inverter with modified hysteresis controller and Total harmonic distortion was found to be 2.98% as shown in

Fig. 6. Figure 7 shows the Modified SIMULINK Model For Real Time Implementation. Figure 8 shows the optimized inverter frequency with adaptive grid connected inverter with modified hysteresis controller which is nearly 10 KhZ. Figure 9 shows that DC bus voltage is nearly 300 volts. Load current, compensated source current, reference current and Filter current of Adaptive Grid interactive Inverter with Modified Hysteresis controller is shown in Fig. 10. A comparison of Grid connected Inverter with conventional hysteresis controller, with and without adaptive control is shown in Table 4.

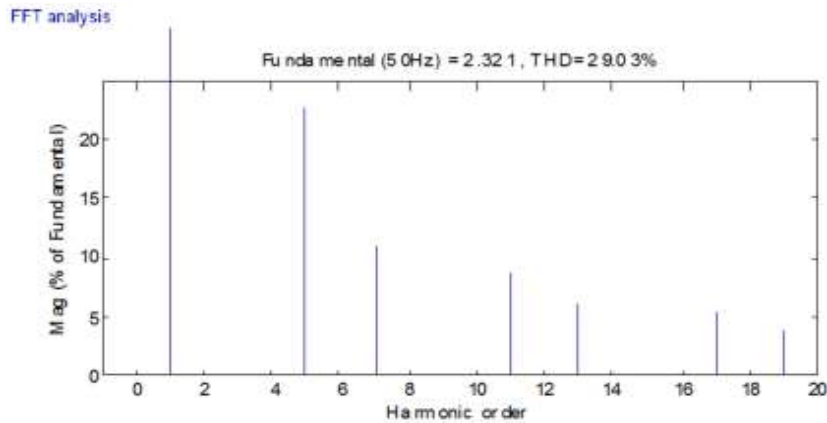


Fig. 3: THD of uncompensated source current



Fig. 4: Hardware setup for REALTIME implementation

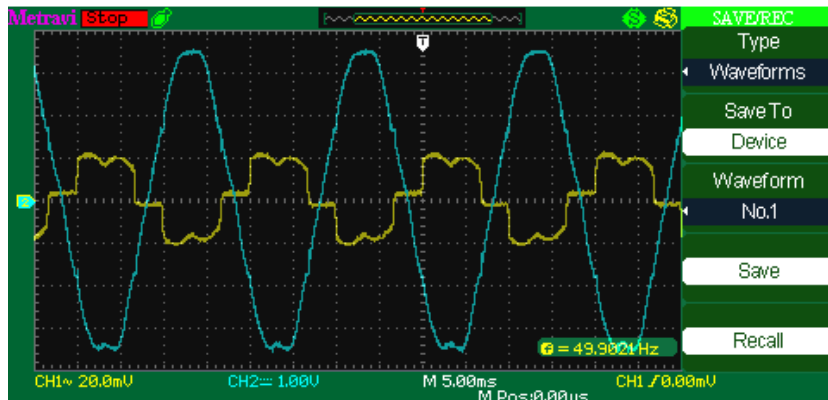


Fig. 5: Source current before and after compensation

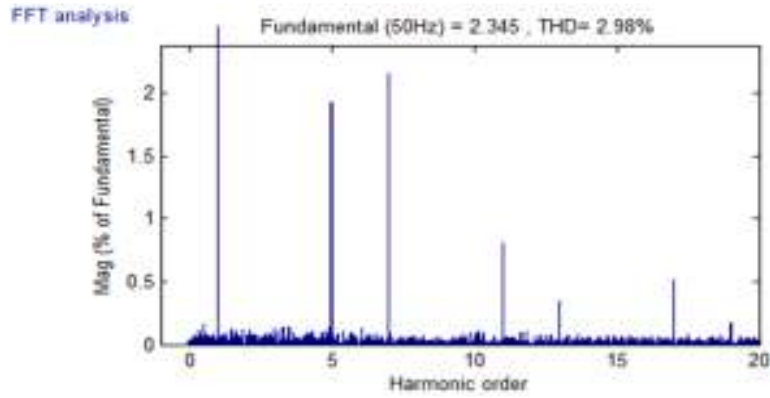


Fig. 6: THD of compensated source current of adaptive minimally switched grid connected inverter with modified hysteresis control

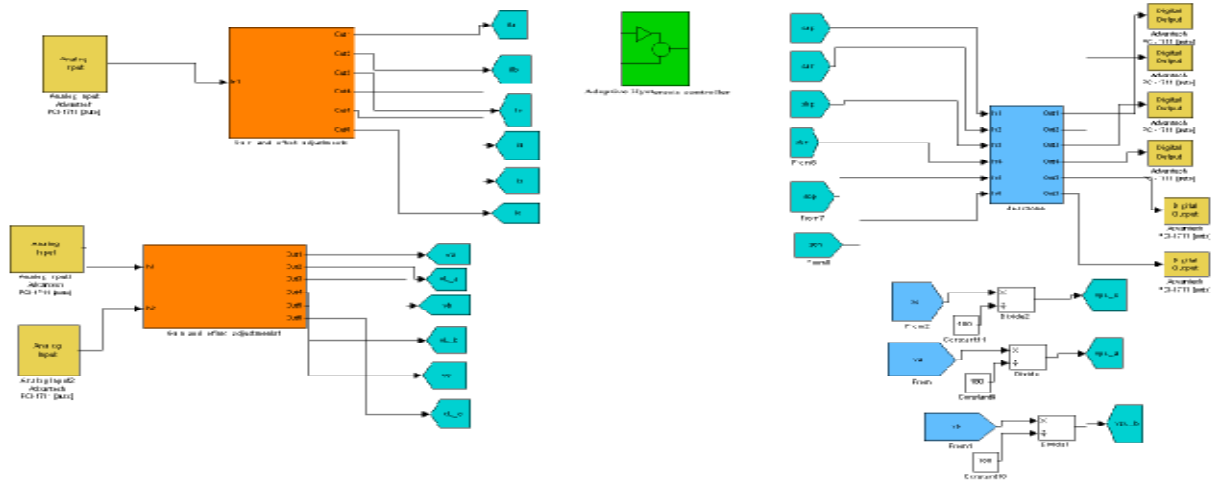


Fig. 7: Modified MATLAB SIMULINK model for REALTIME implementation

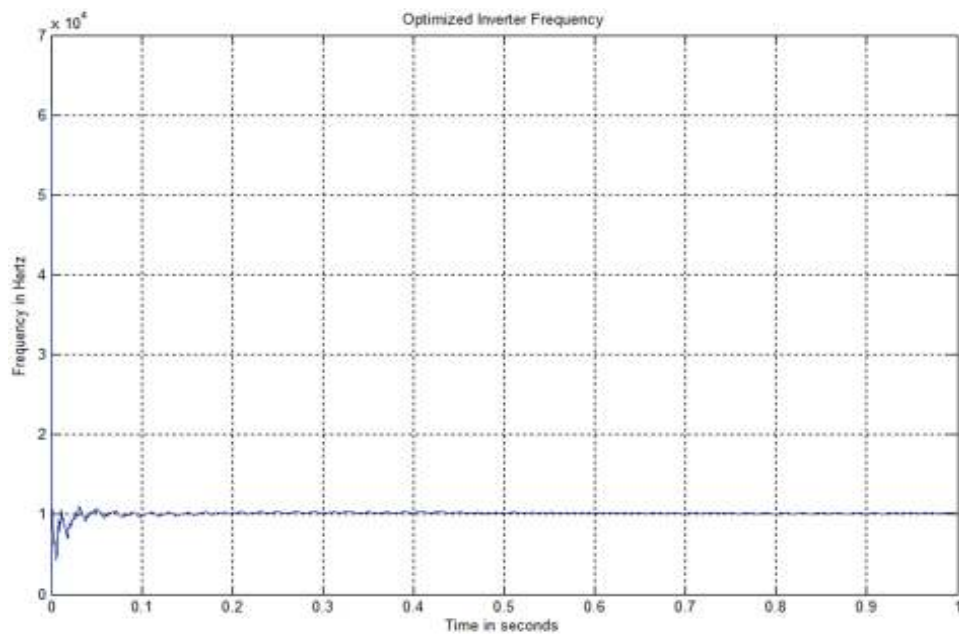


Fig. 8: Optimized inverter frequency with adaptive grid connected inverter with modified hysteresis controller

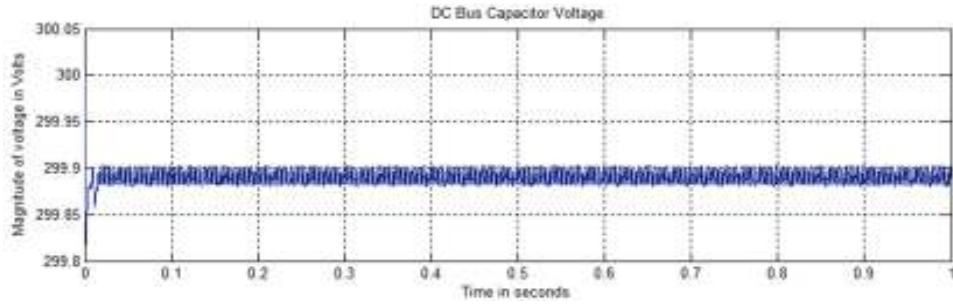


Fig. 9: DC bus capacitor voltage

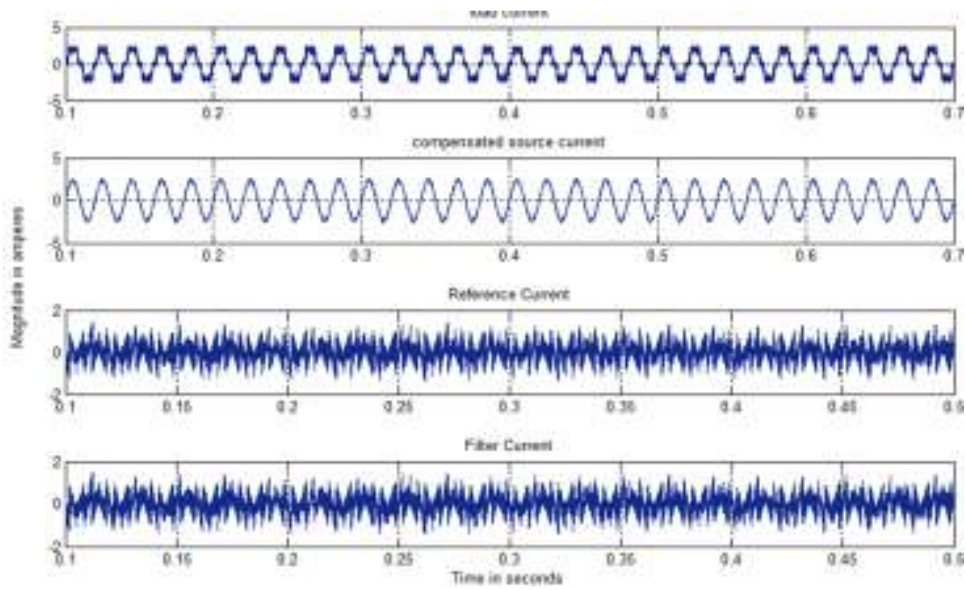


Fig. 10: Load current, compensated source current, reference current and filter current of adaptive minimally switched grid interactive inverter

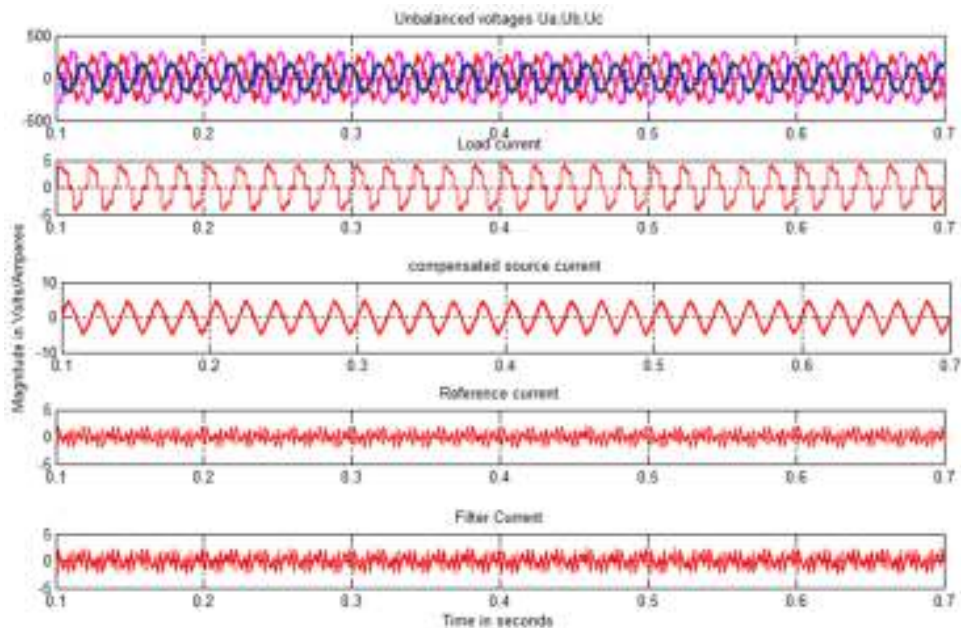


Fig. 11: Response of adaptive minimally switched grid connected inverter to unbalanced source voltages

Table 4: Comparison of conventional and modified hysteresis controller

Current controller used	THD of supply current (%)	Switching frequency	Switching losses
Conventional hysteresis controller	5.15	Variable	Increased switching losses since all the six switches of the three phase inverter are controlled at high frequency.
Modified hysteresis controller	7.82	Variable	Switching losses reduced to one-third since only two switches are controlled at a time when compared to conventional hysteresis controller.
Conventional hysteresis controller with adaptive control	3.68	Reduced and nearly constant	Increased switching losses since all the six switches of the three phase inverter are to be controlled, even though the switching frequency is low, when compared to that of conventional type.
Modified hysteresis controller with adaptive control	2.98	Reduced and nearly constant	Switching losses reduced to one-third since only two switches are controlled at a time and switching frequency is reduced when compared to that of conventional type.

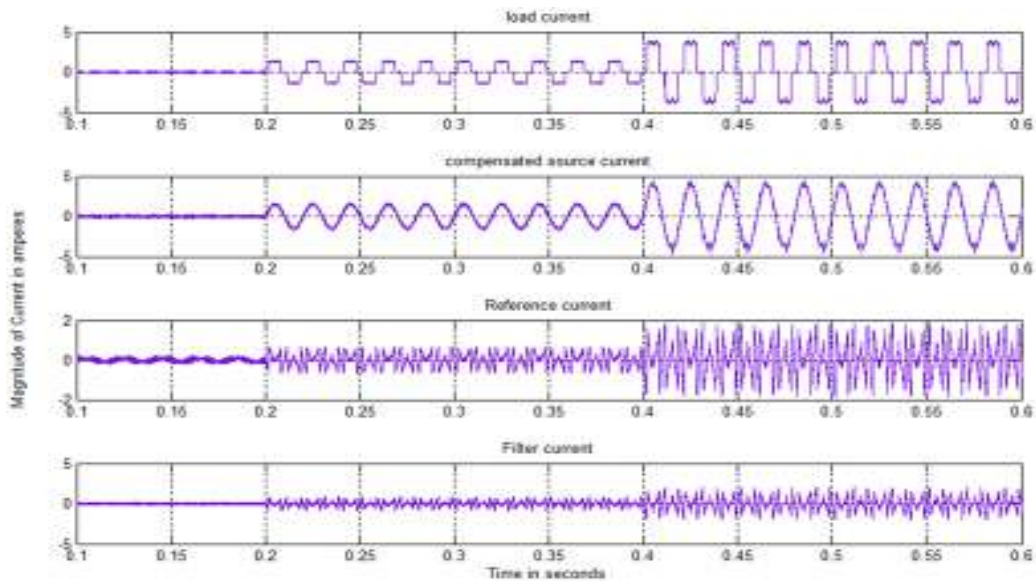


Fig. 12: Dynamic response of adaptive minimally switched grid connected inverter with modified hysteresis controller

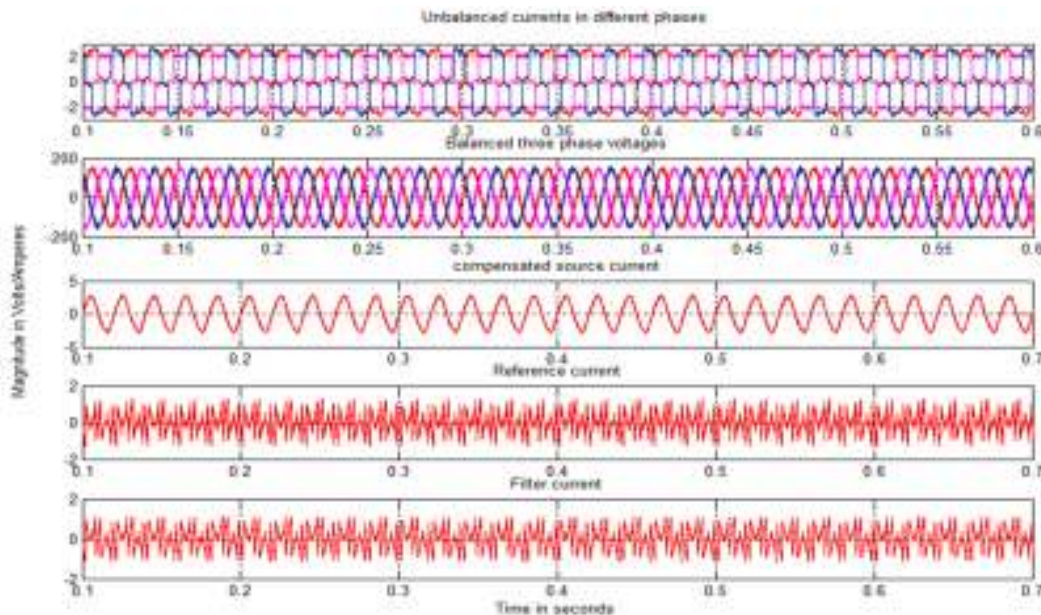


Fig. 13: Response of adaptive minimally switched grid interactive inverter to unbalanced load conditions

The effectiveness of Adaptive minimally switched grid connected inverter under unbalanced source voltage conditions was checked by applying a voltage imbalance in phases b and c. Voltages of phases a, b and c were 230, 300 and 160 volts, respectively. Figure 11 depicts the unbalance in source voltages U_a , U_b and U_c along with load current, compensated source current, reference current and Filter current of phase a. Dynamic performance under change in load with filter is depicted in Fig. 12. Change in load occurs at $t = 0.2$ sec and $t = 0.4$ sec.

Figure 13 shows the response of Adaptive minimally switched grid connected inverter to unbalanced load conditions. An imbalance in load currents was introduced by connecting a single phase diode rectifier feeding a resistive load between phases a and c.

CONCLUSION

Adaptive minimally switched grid connected inverter in which switching losses are reduced to one third of that of the conventional controller, can be successfully employed for making the switching frequency of the inverter nearly constant, thereby overcoming the disadvantage of conventional and modified hysteresis controller which has variable switching frequency. Employing Adaptive control, significant reduction in THD of supply current is obtained at reduced inverter frequency. THD is reduced from 29.03% when uncompensated to 2.98% when compensated which is well within the limits. Reduction in instantaneous switching frequency obtained through adaptive control reduces the switching losses further. Good Dc bus voltage stabilization is also achieved since bus voltage is maintained nearly at 300 volts. Switching frequency of the inverter and THD of source current is optimized with adaptive control. The Minimally switched grid connected inverter with adaptive modified hysteresis controller works well under unbalanced source and load conditions also.

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