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Reactive Power Compensation in Inverter Interfaced Distributed Generation

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Abstract - The consumption of reactive power is stochastic in nature for the distribution system. This uncertain variation of the reactive power leads to 1) Variation of voltage at the point of common coupling(PCC) 2)Low power factor 3)low efficiency 4) improper utilization of distribution system and 5) loss of synchronism for a grid connected inverter based – distributed generation. Now a day's distributed generation (DG) system uses current regulated PWM voltage-source inverters (VSI) for synchronizing the utility grid with DG source in order to ensure the grid stability. In this paper reactive power compensation based hysteresis controller and adaptive hysteresis controller is analyzed for inverter interfaced DG which can control the active and reactive power independently. The adaptive hysteresis controller can reduce the current harmonic at PCC considerably which ensures lower total harmonic distortion (THD). The performance indices include THD of the grid current, fast current tracking during steady state and transient conditions. The studied system is modeled and simulated in the MATLAB Simulink environment.

Index Terms-Adaptive hysteresis current control, distributed generation (DG), voltage source inverter (VSI), utility grid, total harmonic distortion (THD).

I. NOMENCLATURE

I_{La}, i_{Lb}, i_{Lc}	: three phase grid current
i_{ld}, i_{lq}	: d and q axis current
ω	: angular frequency
θ	: transformation angle
V_d, V_q	: d-q component of PCC voltage
P_{ref}	: reference value of active power
V_{dc}	: dc-link voltage
V_a, V_b, V_c	: grid voltage per phase
f_c	: modulation frequency
L	: line inductance
V_{pcc}	: voltage at PCC

II. INTRODUCTION :

NDER the restructuring phase of the electric power industry, the traditional vertically integrated utility environment is inevitably being changed. The power system operation will become more competitive and many challenges will arise. Since it is a clean energy source, it has lower impact to the environment, and

never runs out, DG based on renewable and non renewable energy is a hot issue in today competitive market [1].

In conventional generation stations, the generators operate at a fixed speed and thereby with a fixed grid-frequency; however, the dispersed generation presents a quite different and challenging picture. For example, the voltage generated by variable speed wind power generators, PV generators and fuel cells cannot be directly connected to the grid. The power electronic technology plays a vital role to match the characteristics of the dispersed generation units and the requirements of the grid connections, including frequency, voltage, and control. Power electronics is an efficient essential part for the integration of DG unit to achieve high efficiency and performance in power systems [2].

One important part of the distributed system is its control. The control tasks can be divided into two major parts. 1) Input-side controller, with the main property to extract the maximum power from the input source. 2) Grid-side controller, which can have the task like, control of active power generated to the grid, control of reactive power transfer between the DPGS and the grid; control of dc-link voltage, ensure high quality of the injected power, grid synchronization [3]

The current-controlled PWM-VSI is usually preferred for inter-facing DG to the utility grid as it has quick response and accurate control. Basically, a current controller forces the load current to follow the current command in some power apparatus. Current controller techniques have become an intensive research subject because they offer substantial advantages in eliminating the dynamics in high-performance ac drive systems under field-orientation control. The common strategies of current controllers can be classified as ramp comparator, hysteresis controller, and predictive controller.[4]

The ramp-comparator controller compares the error current signal to a triangular carrier waveform to generate the inverter firing pulses. The main advantage of the ramp comparison technique is that the inverter switching's usually limited to the frequency of the triangular waveform, and the produced harmonics are defined at a fixed frequency. However, the system response is affected by the stability requirements of the feedback loop, which also depends on load parameters. Thus, inherent phase and amplitude errors arise, even in the steady state condition. Predictive controllers calculate the inverter voltage required to force the currents to follow the current references. Although it gives optimum performance in terms of both response time and accuracy, it takes more calculations and requires a good knowledge of the load parameters. In a hysteresis current controller, the hysteresis comparators are used to impose a dead band or hysteresis around the reference current. The hysteresis control scheme provides excellent dynamic performance because it acts quickly. However, the main disadvantage is the variation of the switching frequency. [5][6].

In the distribution system the major loads are non unity power factor reactive load which draw a reactive power component of current along with a active power. This reactive power component of current causes low power factor, low efficiency and poor utilization of the distribution system [7].

The objective of this article is to compensate the reactive power during the variation of load demand along with independent control of active and reactive power. The performances of the system is analyzed by the implementation of the hysteresis and adaptive hysteresis current controller

The paper is organized as follows – current control strategies in grid connected system are given in section II. Single-phase grid connected VSI is described in section III. Analysis of hysteresis and adaptive current controller is explained in the section IV. Section V dedicated to results and discussion, followed by conclusion in section VI. references in section VII.

III. CURRENT CONTROL STRATEGIES IN GRID CONNECTED VSI SYSTEM

A current controlled VSI is generally used to synchronize the utility grid with the distributed generation as shown in Fig.1.

Fig. 1 : Three phase inverter connected to utility grid

The control loop comprises either hysteresis or adaptive Hysteresis current controller in the inner loop. The converter manages the amount of Inverter injected to the PCC bus. The load current, I_L is converted from the three phase coordinates to the synchronously rotating frame by using equation (1), where θ is the instantaneous angle of the PCC voltage vector, obtained from phase locked loop (PLL) circuit.

$$\begin{bmatrix} i_{ld} \\ i_{lq} \\ i_{l0} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\alpha) & \cos(\alpha - (2\pi/3)) & \cos(\alpha + (2\pi/3)) \\ \sin(\alpha) & -\sin(\alpha - (2\pi/3)) & -\sin(\alpha + (2\pi/3)) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} X \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \quad (1)$$

Fig. 2 : Block diagram for current control of three-phase grid-connected VSI

Fig. 3 : Block diagram of PLL

The adjustment of the dq-transformation is so that the voltage at the PCC has no q-axis component. A PI regulator controls the angular frequency by (2). Then the transformation angle can be determined by (3).

$$\omega = k_p^{PLL} v_q + k_i^{PLL} \int (v_q \times dt) \quad (2)$$

$$\theta = \int (\omega \times dt) \quad (3)$$

It is assumed that there is no path for the zero sequence components, therefore i_0 in (1) and v_0 in Fig.3 can be ignored. However, these variables have been considered in the formulation to present the general case.

The resultant q-component is responsible for the reactive power flow through the utility network. To compensate the reactive component the quadrature component (i.e., i_{qref}) of the reference current of VSI, $I_{Inverter}$, equal to the quadrature component (i.e., i_{iq}) of the load current (I_{Load}).

The generated active power of DG is expressed by the $P = v_d \times i_d + v_q \times i_q$ (4)

$$v_d = v_{PCC} \ \& \ v_q = 0 \quad (5)$$

Hence

$$I_d = \frac{P}{V_{PCC}} \quad (6)$$

Selecting the reference active power of DG as the command signal given of the utility the equation (6) can be rewritten, as follows:

$$I_{dref} = \frac{P_{ref}}{V_{PCC}} \quad (7)$$

Where i_{dref} is the direct component of the reference current of the VSI, $I_{Inverter}$. This component is also responsible for the losses in both the converter and the capacitor. Finally, applying inverse dq transformation rotating at the supply frequency ω by the equation (8),

the three-phase VSI reference currents are determined from the d-q reference components [8].

$$\begin{bmatrix} i_{aref} \\ i_{bref} \\ i_{cref} \end{bmatrix} = \begin{bmatrix} \sin(\omega t) & \cos(\omega t) & 1 \\ \sin(\omega t - (2\pi/3)) & \cos(\omega t - (2\pi/3)) & 1 \\ \sin(\omega t + (2\pi/3)) & \cos(\omega t + (2\pi/3)) & 1 \end{bmatrix} X \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (8)$$

IV. ANALYSIS OF HYSTERESIS AND ADAPTIVE HYSTERESIS CURRENT CONTROLLER

The hysteresis band current control technique has proven to be most suitable for all the applications of current controlled voltage source inverters. The hysteresis band current control is characterized by unconditioned stability, very fast response, and good accuracy. On the other hand, the basic hysteresis technique exhibits also several undesirable features; such as uneven switching frequency that causes acoustic noise and difficulty in designing input filters. The conventional hysteresis band current control scheme used for the control of grid connected line current is composed of a hysteresis around the reference line current [9]. By notice equation (9) the reference line current of the grid connected inverter is referred to as i_{ref} , measured line current of the grid connected inverter is referred to as i and difference between i and i_{ref} is referred to as δ . The hysteresis band current controller assigns the switching pattern of grid connected inverter.

$$\delta = i - i_{ref} \quad (9)$$

The switching logic is formulated as follows:

If $\delta > HB$ upper switch is OFF and lower switch is ON

$$(S_4=1, S_1=0).$$

If $\delta < -HB$ upper switch is ON and lower switch is OFF

$$(S_4=0, S_1=1).$$

The switching logic for phases B and C is similarly, using corresponding reference and measured currents and hysteresis bandwidth (HB).

In case of hysteresis band current control the rate of change of the line current vary the switching frequency, therefore the switching frequency does not remain constant throughout the switching operation, but varies along with the current waveform. Furthermore, the line inductance value of the grid connected inverter and the dc link voltage are the main parameters determining the rate of change of grid connected inverter line currents.

On the other hand The adaptive hysteresis band current controller changes the hysteresis bandwidth according to instantaneous current variation (di_{aref}/dt)

and V_{dc} voltage to minimize the influence of current distortion on modulated waveform.

Fig.4. shows the PWM current and voltage waveforms for phase A. The currents i_a tends to cross the lower hysteresis band at point 1, where S_1 is switched on.

The linearly rising current (i_a^+) then touches the upper band at point P, where is S_4 switched on. The following equations can be written in the respective switching intervals t_1 and t_2 from Fig.4.

Fig. 4 : Current and voltage wave with hysteresis band current control

$$di_a^+ = \frac{1}{L}(0.5V_{DC} - V_a) \quad (10)$$

$$di_a^- = -\frac{1}{L}(0.5V_{DC} + V_a) \quad (11)$$

From fig.3

$$\frac{di_a^+}{dt}t_1 - \frac{di_{aref}}{dt}t_1 = 2HB \quad (12)$$

$$\frac{di_a^-}{dt}t_2 - \frac{di_{aref}}{dt}t_2 = -2HB \quad (13)$$

$$t_1 + t_2 = T_c = \frac{1}{f_c} \quad (14)$$

Where t_1 and t_2 are the respective switching intervals and f_c is the switching frequency.

Adding equation (12) and (13) and substituting in equation (14) we can write

$$\frac{di_a^+}{dt}t_1 + \frac{di_a^-}{dt}t_2 - \frac{1}{f_c} \frac{di_{aref}}{dt} = 0 \quad (15)$$

Subtracting equation (13) from (14)

$$\frac{di_a^+}{dt}t_1 - \frac{di_a^-}{dt}t_2 - (t_1 - t_2) \frac{di_{aref}}{dt} = 4HB \quad (16)$$

Substituting equation (11) in (16)

$$(t_1 + t_2) \frac{di_a^+}{dt} - (t_1 - t_2) \frac{di_{aref}}{dt} = 4HB \quad (17)$$

Substituting equation (11) in equation (15) and solving

$$(t_1 - t_2) = \frac{di_{aref}/dt}{f_c(di_a^+/dt)} \quad (18)$$

Substituting equation (18) in (17)

$$HB = \frac{0.125V_{DC}}{f_c L} \left[1 - \frac{4L^2}{V_{DC}^2} \left(\frac{V_a}{L} + m \right)^2 \right] \quad (19)$$

Where f_c is modulation frequency, $m = di_{aref}/dt$ is the slope of command current wave. Hysteresis band (HB) can be modulated at different points of fundamental frequency cycle to control the switching pattern of the inverter. For symmetrical operation of all three phases, it is expected that the hysteresis bandwidth (HB) profiles HB_a , HB_b and HB_c will be same, but have phase difference.

Fig. 5 : The adaptive hysteresis band width calculation block diagram

From the equation (19) we can conclude that the adaptive hysteresis band is a function of current variation di_{aref}/dt and V_{dc} .

Fig. 6 : Variable Hysteresis band current controller

V. RESULTS & DISCUSSION

The section reveals the simulation results for hysteresis and adaptive hysteresis current control algorithm applied to three-phase mains connected inverter system. The studied model has been developed and simulated in the MATLAB/simulink environment. For simulation, the Dc-link voltage is taken 600V, and the grid voltage is 400V (L-L). the modulation frequency is taken 10KHz and the command value of power is set to 3.5Kw.

A. Steady State Analysis

Fig.7and 8 shows the steady state response of hysteresis and adaptive hysteresis current controller. In steady state the reactive power demand of the load is kept very small.fig.7 (e) and 8(e) shows that active power is equal to the input command value 3.5 Kw. The active power demand of the load is more than the command value. The deficit power to the load is supplied by the utility grid. fig.7(c) and 8(c) shows the load current (dotted line) and the inverter current per phase.

Fig. 7 : Simulation result of the steady-state response of hysteresis current controller (a) grid voltage at VPCC (b) grid current (c) Inverter output phase current and load current (d)Dc-link voltage (e)Reactive power(f)Active power(g) Quadrature component of inverter current.

Fig. 8 : Simulation result of the steady-state response of adaptive hysteresis current controller (a) grid voltage at VPCC (b) grid current (c) Inverter output phase current and load current (d)Dc-link voltage (e)Reactive power(f)Active power(g) Quadrature component of inverter current

Fig.9 shows the adaptive hysteresis band width for a constant load.

Fig. 9 : Adaptive hysteresis band

B. Transient Analysis

Fig.10 and 11shows the transient response of hysteresis and adaptive hysteresis current controller. In this reactive power demand of the load is increased between a period 0.08 sec to 0.14 sec. fig.10 (b) and 11(b) shows that the inverter current is increasing due to the increase of reactive power load demand.

Fig.10 : Simulation result of the transient response of hysteresis current controller (a) grid voltage at VPCC (b) grid current (c) Inverter output phase current and load current (d)Dc-link voltage (e)Reactive power(f)Active power(g) Quadrature component of inverter current

In described control scheme the PWM-VSI is able to inject the reactive power when the load demand increases which can be analyze by observing Fig10 (f) and 11(f).As far as the active power is concerned Fig 10(e) and 11(e) shows that the active power is almost constant and equal to the input command value (3.5Kw). Fig. 10(g) and 11(g) shows the quadrature component of the inverter current under dynamic change in the load reactive power.

Fig. 11 : Simulation result of the transient response of adaptive hysteresis current controller (a) grid voltage at VPCC (b) grid current (c) Inverter output phase current and load current (d)Dc-link voltage (e)Reactive power(f)Active power(g) Quadrature component of inverter current

Fig. 12 : Adaptive hysteresis band

As the hysteresis band is function of di_{aref}/dt and V_{DC} hence the band width changes according to the variation of load. by changing the band width the user can control the average switching frequency of the grid connected inverter.

Fig. 13 : Response of reference current, actual current and current error for hysteresis current controller

The dynamic response of the hysteresis current controller is better than adaptive hysteresis controller but the current error is more in case of hysteresis current controller as shown in fig. 13 as compared to adaptive hysteresis current controller shown in Fig .14.

Fig. 14 : Response of reference current, actual current and current error for adaptive hysteresis current controller.

Fig. 15 : THD of grid current for hysteresis current controller

Fig. 16 : THD of grid current for adaptive hysteresis current controller

Finally, the current harmonic spectrum for Adaptive hysteresis current control method is shown in Fig.16. The THD is 1.72% which is less than THD of hysteresis current controller. THD of hysteresis current controller is 1.79% which is given in Fig.15.

VI. CONCLUSIONS

This paper described the dynamic performance of adaptive hysteresis current controller for grid connected inverter system during load variations. The study includes independent control of active and reactive power of the utility end, harmonic current reduction via current error minimization and lesser THD at the PCC. From the study we observed that, adaptive hysteresis current controller can enable to reduce the current error at load terminal, thus in turn it reduces the THD of load current and it provides nearly constant switching frequency of operation by adjusting its hysteresis-band. In addition, we also observed that the voltage profile at PCC can be maintained constant irrespective of the variation of the reactive power consumption and it reduces the EMI effects, which are the important requirements of the distribution system to satisfy the sensitive loads like medical equipments etc.

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