Adaptive Backstepping Control Technique for Single Phase Shunt Active Power Filters

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***Abstract*: In this paper, a cascade two-loop non-linear controller is proposed for single-phase shunt active power filters which is robust and stable in a wide range of output current and DC-link voltage changes. A variable structure proportional–integral controller (VS-PI) is designed to regulate DC-link voltage in the outer loop. Also filter output current is controlled in the inner loop using adaptive backstepping approach. All of the model uncertain parameters are estimated using designed estimation rules. By introduction of suitable Lyapunov functions, proposed controller stability is investigated using Barbalat lemma. Grid reference current is calculated indirectly using a phase-locked loop (PLL) circuit according to DC-link voltage error. By simulation result it is shown that the proposed controller is able to eliminate harmonic components of the local load current with a fast dynamic response.**

***Keywords*: PCC; PLL; PI controller; PWM; SAPF; THD**

I. INTRODUCTION

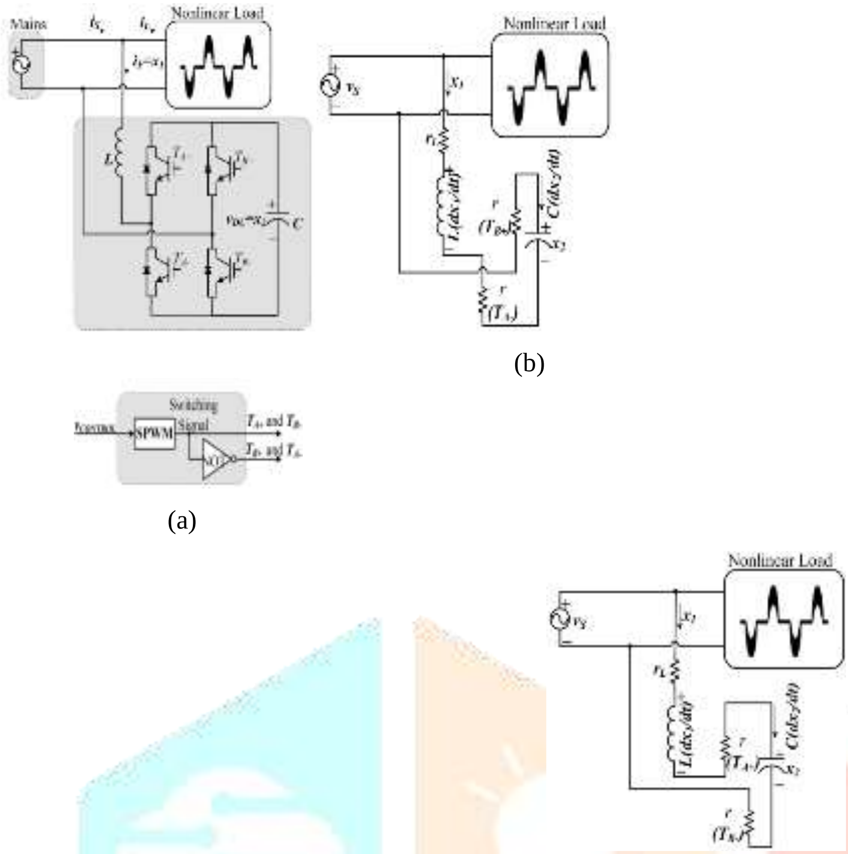
Harmonics are caused by the use of non- linear loads, such as switch-mode power converters, power-electronics-operated adjustable-speed drives, fluorescent lamps, arc furnaces, welding equipment, and other nonlinear loads used in both domestic and industrial applications. The presence of harmonics in the system results in several effects such as increased heating losses in transformers, motors, and lines; low power factor and poor utilization of distribution wiring and plant. In response to the power quality concerns of typical power distribution systems in terms of harmonic current distortion and power factor IEEE 519 and IEC EN 61000-3 standards specify regulations governing harmonic compliance. Due to presence of current harmonics in power grid may lead to reduction of voltage quality at point of common coupling (PCC). For this reason, electric consumers, which are located in the neighbourhood of non-linear loads, will be affected by harmonics. Load current harmonics can be filtered easily by using conventional passive filters. But resonance problems are the main disadvantages of the passive filters.

In recent years, grid connected inverters (GCIs) have found various applications. The inverter is connected in parallel between the power grid and local loads. Such application of the GCI is named shunt active power filter (SAPF).).Shunt filters are the most widely used solution, as they efficiently eliminate current distortion and the reactive power produced by nonlinear loads. Several control methods have been reported to control shunt active power filters. In direct control method usually SAPF includes three different control blocks. The reference calculation unit performs online calculations of the local loads reactive current and harmonic components. The current control unit applies appropriate switching signals in order that inverter output current follows the reference value. The DC-link voltage control unit adds an active component to the reference current according to corresponding voltage error. In indirect control method, reference current calculation and DC-link voltage control units are combined together which significantly can reduce required calculations in SAPFs; hence system dynamic response can be improved considerably. In indirect control approach, SAPF includes only two control loops. First, the voltage outer loop which determines grid reference current based on the DC-link voltage error for inner loop. Second, the inner current loop, which controls inverter output current using pulse-width modulation (PWM) switching scheme. Application of the linear controllers in GCI is completely challenging task due to system non-linearity. Hence, application of the non-linear controllers on indirect control of the SAPFs has been used. To estimate uncertain parameters, an adaptive backstepping controller has been designed for the inner current loop of the SAPF. These parameters are coupling inductance and its equivalent series resistance.

In this paper, a two-loop non-linear cascade controller is designed for single-phase SAPFs. The adaptive backstepping controller is developed to control output current of the filter in an inner loop. All of the model uncertain parameters can be estimated using proposed adaptive controller. Furthermore, inverter input DC voltage is regulated in the outer loop using a variable structure (VS) PI controller. Benefits of the both VS and linear controllers are combined in the outer loop of the designed controller. Obviously, according to application of the non-linear controllers in both inner and outer loops, developed SAPF is stable and robust in a wide range of operation. To reduce the effect of power system voltage distortion in load compensation, a single-phase PLL is employed in the outer loop to generate a pure sinusoidal waveform which is in phase with grid voltage.

II. SYSTEM MODEL

The single-phase SAPF is shown in Fig. 1 considering H-bridge inverter. It is assumed that the inverter is switched using bipolar PWM technique. Switching signal (x_g) is obtained by comparison of a high frequency sawtooth waveform (v_{tri}) with the desired AC control signal ($v_{control}$).



(b)

(a)

(c)

Fig. 1 a) Single-phase SAPF circuit; b) System equivalent circuit during active state of the switching signal; c) System equivalent circuit during inactive state of the switching signal

Averaged state-space model of system can be expressed as,

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} \theta_1 & -\theta_2 u \\ \theta_3 u & 0 \end{pmatrix} \quad (1)$$

Where,

$$\theta_1 = -(r_L + 2r/L)$$

$$\theta_2 = (1/L)$$

$$\theta_3 = (1/C)$$

Also, u is the amplitude modulation index of the inverter. Moreover, $X = (x_1, x_2)^T = (i_F, v_{DC})^T$ is state vector of the control system. Considering state-space equations, dynamic model of the single phase SAPF is shown in Fig. 2a

III. Controller Design

As shown in Fig. 2. a VS PI (VS-PI) controller is cascaded with an adaptive backstepping controller for obtaining unity power factor in a single-phase SAPF. This combined controller purely filters out the loads current harmonics. In fact, harmonic components are taken from the main and transferred to the SAPF. In this condition, grid current would be completely sinusoidal and in phase with the utility voltage.

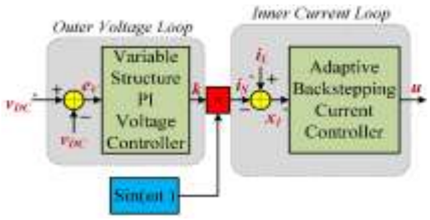


Fig. 2 Block diagram two loop controller

$$i_s^* = i_s = k \sin\theta \quad (2)$$

In this equation, k is a constant coefficient, it is depends on local load active power consumption and is reference value of the grid current, sin θ is generated using a single-phase PLL. The value of the k can be determined in an outer loop according to DC-link voltage error. The VS-PI controller generates the fundamental reference current that is absorbed by the non-linear load. Only small part of the fundamental current taken from the main is absorbed by the voltage source SAPF to cover the power losses and the rest of the fundamental current is forwarded to the non-linear load.

A. Outer-loop design

This loop adjusts grid reference current () and subsequently determines filter reference current so that the DC-link voltage be equal to its reference value ().VS-PI controller consists of a first-order derivative type sliding mode controller in parallel with a linear conventional PI controller The VSPI controller produces the factor k for generation of the fundamental reference current that is observed by the non-linear load.

$$k = [e_v + K_{VSC}\,sgn(S_V)]\left(K_P + \frac{K_I}{s}\right) \qquad (3)$$

Where and are the PI controller gains and α and are gains of the VS controller. The gains of the mentioned controller should be large enough to compensate for modelling uncertainties and perturbations. In this case, α and are selected by trial and error method as large as needed to obtain the desired performance in terms of robustness and chattering.

B. Inner controller – current loop design

This controller adjusts converter switching signal to regulate filter output current in its corresponding reference value In this case, all of the reactive and harmonic components of load current will be supplied by SAPF.It is clear that system model parameters are uncertain. So the controller is developed so that all of the model's impedances can be estimated using some appropriate estimation rules. The adaptive backstepping controller for single-phase SAPF is designed in two steps as follows.

First step: Considering filter reference current value ( ), the current error is defined as

$$z_1 = x_1 - x_1^* \qquad (4)$$

According to (1) and (4), it is possible to write derivative of the first error variable as,

$$\dot{z}_1 = \dot{x}_1 - \dot{x}^*_1 \Rightarrow \dot{z}_1 = \theta_1 x_1 - \theta_2 u x_2 + \theta_2 v_s - \dot{x}^*_1 \qquad (5)$$

Considering uncertain parameters of the model (θ_i ;i = 1 − 3).

Hence, (5) can be rewritten as below:

$$\dot{Z}_1 = \hat{\theta}_1 x_1 - \hat{\theta}_2 \theta^2 u x_2 + \hat{\theta}_2 v_s - \dot{x}^*_1 + (\theta_1 - \hat{\theta}_1)x_1 - (\theta_2 - \hat{\theta}_2)u x_2 + (\theta_2 - \hat{\theta}_2)v_s \qquad (6)$$

By defining the uncertain parameters vector, (5) can be rewritten as;

$$\dot{z}_1 = \hat{\theta}^T \Phi_1 - \dot{x}_1 + (\theta - \hat{\theta})^T \Phi_1 \qquad (7)$$

Where Φ_1 should be defined as;

$$\Phi_1^T = [x1 \quad (-u x_2 + v_s) \quad 0] \qquad (8)$$

To investigate stability of the system, first Lyapunov function is defined as;

$$V_1 = \frac{1}{2}[z_1^2 + (\theta - \hat{\theta})^T \Gamma^{-1} (\theta - \hat{\theta})] \qquad (9)$$

Where in this equation, Γ is a 3 × 3 diagonal matrix which diagonal elements are called y_{ii} time derivative of the first Lyapunov function can be obtained as;

$$\dot{V}_1 = z_1 \dot{z}_1 + (\theta - \hat{\theta})^T \Gamma^{-1}(-\dot{\hat{\theta}}) \qquad (10)$$

By replacing (7) into (10), the following equation can be obtained as;

$$\dot{V}_1 = z_1(\hat{\theta}^T \Phi_1 - \dot{x}^*_1) + (\theta - \hat{\theta})^T \Gamma^{-1}(-\dot{\hat{\theta}} + \Gamma z_1 \Phi_1) \qquad (11)$$

In (12), if it is assumed that ($\hat{\theta}^T \Phi_1 - \dot{x}^*_1$) is equal to ($-c_1 z_1$), and $(-\dot{\hat{\theta}} + \Gamma z_1 \Phi_1)$ is equal to zero, then $\dot{V}_1 = -c_1 z_1^2$ will be obtained which is a negative semi-definite function and ensures asymptotical stability of the system. In these equations, c_1 is a positive design scalar.

Second step: To defined as the second error variable:

$$z_2 = \hat{\theta}^T \Phi_1 - \dot{x}^*_1 - (-c_1 z_1) \qquad (12)$$

Derivative of the first error variable can be written by combining (7) and (12) as;

$$\dot{z}_1 = -c_1 z_1 + z_2 + \qquad (13)$$

According to (1), (5) and (8), time derivative of the second error variable can be obtained from (12) as;

$$\dot{z}_2 = A + \hat{\theta}^T \Phi_2 + (\theta - \hat{\theta})^T \Phi_2 \qquad (14)$$

Where in this equation

$$A = \dot{\hat{\theta}}_1 x_1 + \dot{\hat{\theta}}_2 - u x_2 + v_s - \dot{u}\,\hat{\theta}_2 x_2 + \dot{\hat{\theta}}_2 v_s - \ddot{x}^*_1 - c_1 \dot{x}^*_1 \qquad (15)$$

$$\Phi^T{}_2 = [(\hat{\theta}_1 + c_1)x_1 \quad (\hat{\theta}_1 + c_1)(-u x_2 + v_s) - u^2 \hat{\theta}_2 x_2] \qquad (16)$$

In the second step, Lyapunov function can be considered as follows:

$$V_2 = \frac{1}{2}[z_1^2 + z_2^2 + (\theta - \hat{\theta})^T \Gamma^{-1}(\theta - \hat{\theta})] \quad (17)$$

Hence, time derivative of will be obtained as

$$\dot{V}_2 = z_1\dot{z}_1 + z_2\dot{z}_2 + (\theta - \hat{\theta})^T \Gamma^{-1}(-\dot{\hat{\theta}}) \quad (18)$$

By substitution $\dot{z}_1$ and $\dot{z}_2$ from (13) and (14), $\dot{V}_2$ will be simplified as,

$$\dot{V}_2 = -c_1 z_1^2 + z_1 z_2 + z_2(A + \hat{\theta}^T \Phi_2) + (\theta - \hat{\theta})^T \Gamma^{-1}(-\dot{\hat{\theta}} + \Gamma z_1 \Phi_1 + \Gamma z_2 \Phi_2) \quad (19)$$

If it is assumed that,

$$A + \hat{\theta}^T \Phi_2 = -c_2 z_2 \quad (20)$$

And

$$-\dot{\hat{\theta}} + \Gamma z_1 \Phi_1 + \Gamma z_2 \Phi_2 = 0 \quad (21)$$

The second Lyapunov function $\dot{V}_2$ will be simplified to $\dot{V}_2 = -c_1 z_1^2 + z_1 z_2 - c_2 z_2^2$ Now, if both design parameters c_1 and c_2 are selected larger than 0.5, time derivative of the second Lyapunov function will be a negative semi-definite function. As a result, it can be concluded that in the developed controller, both error variables z_1 and z_2 are bounded.

Final controller law as well as uncertain parameters estimation rules are achieved as below by replacing (8) and (16) into (20) and (22)

$$\dot{u} = \frac{1}{\hat{\theta}_2 x_2}\{x_1[\dot{\hat{\theta}}_1 + \hat{\theta}_1(\hat{\theta}_1 + c_1) + c_2\hat{\theta}_1 + c_1 c_2 - u^2\hat{\theta}_2\hat{\theta}_3] + x_2[-\dot{u}\hat{\theta}_2 - u\hat{\theta}_2(\hat{\theta}_1 + c_1) - c_2\hat{\theta}_2 u] + v_s[\dot{\hat{\theta}}_2 + \hat{\theta}_2(\hat{\theta}_1 + c_1) + c_2\hat{\theta}_2] + \hat{\theta}_2\dot{v}_s - \ddot{x}_1^* - (c_1 + c_2)\dot{x}_1^* - c_1 c_2 x_1^* \quad (22)$$

$$\dot{\hat{\theta}}_1 = \gamma_{11} x_1[z_1 + z_2(\hat{\theta}_1 + c_1)] \quad (23)$$

$$\dot{\hat{\theta}}_2 = \gamma_{22}(-u x_2 + v_s)[z_1 + z_2(\hat{\theta} \quad (24)$$

$$\dot{\hat{\theta}}_3 = \gamma_3 \quad (25)$$

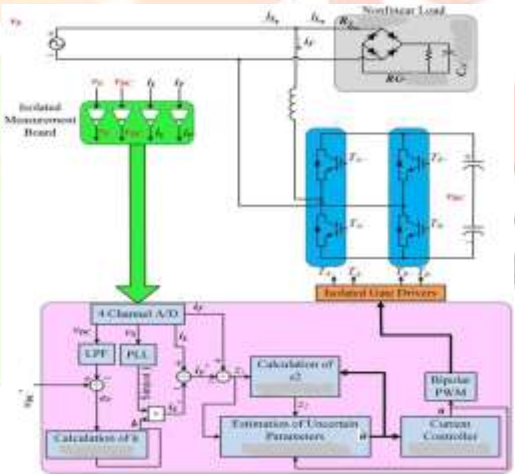
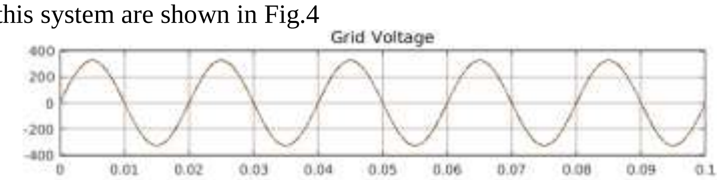


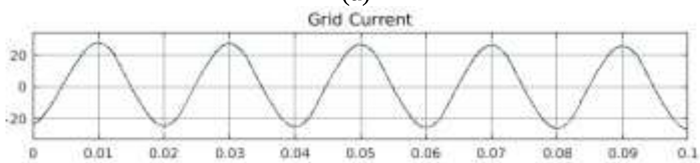
Fig. 3Block diagram of the proposed system

IV. Simulation Result

Circuit topology, nominal values of the system, controller block diagram and experimental setup are illustrated in Fig. 3.The simulation result are taken on this system are shown in Fig.4



(a)



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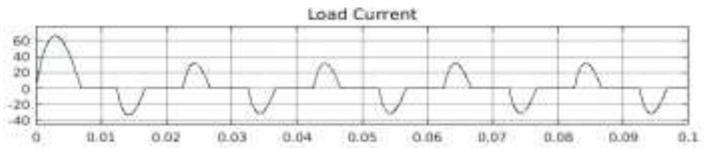

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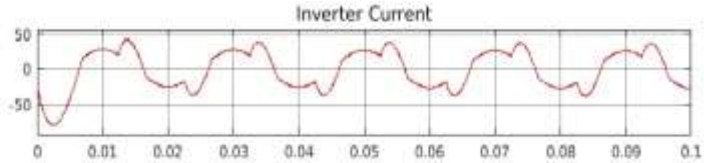

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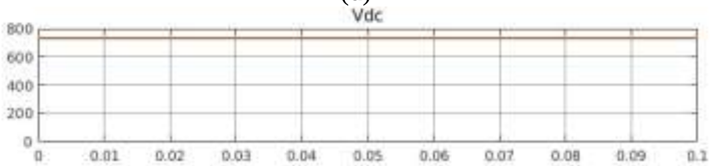

(e)

Fig.4 a)Grid Voltage; b)Grid Current; c)Load Current; d)Inverter Current and e)DC link Voltage

It is seen that in Fig. 5 the grid current THD is equal to 2.68% of proposed SAPF simulation, which is fully compatible with IEEE standards.

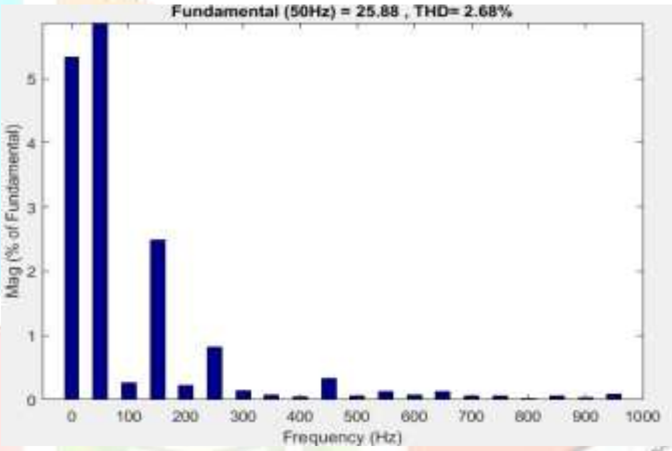

Fig.5 Harmonic Spectrum of the Grid Current

V. Conclusion

Accuracy and effectiveness of the designed nonlinear controller are evaluated It is shown that the developed controller is robust and stable in a wide range of output current and DC-link voltage changes. Also, dynamic response of the SAPF is completely fast during step changes of the reference current. In spite of applying a local load with relatively high THD value proposed controller is able to keep THD of the grid current in the standard range.

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