Shunt Hybrid Power Filter combined with Thyristor-Controlled Reactor for Power Quality Improvement.

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***Abstract*: Harmonics are created by the nonlinear and reactive loads, such as arc furnaces, cycloconverters and motor drives. These harmonics are dangerous to electric power system and destroy the power quality of the system. In order to overcome from this, combination of shunt hybrid power filter (SHPF) and thyristor controlled reactors (TCR) are used. SHPF is a combination of small rating active power filter (APF) and fifth harmonic tuned LC passive filter. APF is mainly used to improve the filtering characteristics and avoids the resonances. The tuned passive filter and TCR form a shunt passive filter (SPF) to compensate reactive power. PI controller is used to extract the required firing angle to compensate the reactive power consumed by the load. The control system mainly consist of inner fast loop for the current control and outer slower one for the voltage control, the model designed based on "instantaneous power theory" the results of simulation satisfies the features described by the theory.**

***Index Terms*—Hybrid powers filter, modeling, nonlinear control, reactive power compensation, shunt hybrid power filter and thyristor-controlled reactor (SHPF-TCR compensator).**

1. INTRODUCTION

The power electronic based equipments are used in industrial and domestic purpose. These equipments have significant impacts on the quality of supplied voltage and these have increased the harmonic current pollution of distribution systems. These equipments have many adverse effects on power system equipments, such as additional losses in overhead and underground cables, transformers and rotating electric machines, problem in the operation of the protection systems, over voltage and shunt capacitor, error of measuring instruments, and malfunction of low efficiency of customer sensitive loads. Hybrid power filters have been introduced and implemented in practical system applications. Shunt hybrid filter consists of an active filter which is connected in series with the passive filter and with a three phase PWM (pulse width modulation) inverter. This filter effectively mitigates the problems associated with passive and active filters. It provides cost effective harmonic compensation, particularly for high power nonlinear load. Different control techniques are present for extracting harmonic components of the source current, Some of them are synchronous reference frame (SRF) transformation, instantaneous power (p-q) theory, etc. Where high pass filters (HPFs) are used for extracting harmonic components of the source current from the fundamental components.

A shunt hybrid power filter (SHPF) is modeled in the stationary "a-b-c" reference frame and then, the model is transformed into the rotating "d-q" reference frame to reduce the control complexity. Decoupled current control techniques using proportional–integral (PI)-type controller is implemented to force the current of the filter to track their reference value. On the other hand the dc-voltage of the filter is regulated using P-I controller. The harmonic current of the non-linear load is controlled by feeding it to the passive filter; hence no harmonic currents are drawn from the ac mains. LC passive filter is connected with an active filter, the required rating of the active filter is much smaller than that of a stand-alone shunt active filter. Here switching ripple filter is not required because its LC circuit accomplishes the filtering of the switching ripple. Simulation results of PI controller scheme are observed and it confirms the effectiveness of the SHPF in damping and mitigation of harmonics.

2. MODELING AND CONTROL STRATEGY.

SHPF

The shunt hybrid power filter (SHPF) contains the three phase supply voltage, three phase diode rectifier. The filtering system consists of a small-rating active power filter connected in series with the LC passive filter. This configuration of hybrid filter ensures the compensation of the source current harmonics by enhancing the compensation characteristics of the passive filter besides eliminating the risk of resonance. It provides effective compensation of current harmonics and limits supply voltage distortion. The hybrid filter is controlled such that the harmonic currents of the nonlinear loads flow through the passive filter and that only the fundamental frequency component of the load current is to be supplied by the ac mains.

2.1 Modeling of SHPF

The system equations can be written by using Kirchhoff's voltage law

$$v_{s1} = L_{PF}\frac{di_{c1}}{dt} + R_{PF}i_{c1} + v_{CPF1} + \mathrm{v}_{1\mathrm{M}} + \mathrm{v}_{\mathrm{MN}}$$
$$v_{s2} = L_{PF}\frac{di_{c2}}{dt} + R_{PF}i_{c2} + v_{CPF2} + v_{2M} + v_{MN}$$
$$v_{s3} = L_{PF}\frac{di_{c3}}{dt} + R_{PF}i_{c3} + v_{CPF3} + v_{3M} + v_{MN}$$

$$\frac{\mathrm{dv_{dc}}}{\mathrm{dt}} = \frac{1}{\mathrm{C_{dc}}}\mathrm{i_{dc}} \qquad (1)$$

The k^{th} value of switching function *ck*, for *k* = 1, 2, 3 is defined as

$$c_k = \begin{cases} 1, \text{if } \mathrm{s_k} \text{ On and } \mathrm{s_k'} \text{is Off} \\ 0, \text{if } \mathrm{s_k} \text{ Off and } \mathrm{s_k'} \text{is On} \end{cases} \qquad (2)$$

A switching state function *d*nk is defined as

$$d_{nk} = (C_k - \tfrac{1}{3}\textstyle\sum_{m=1}^{3} C_m)\, n \qquad (3)$$

Due to the absence of the zero sequence in the ac voltages and current in [*d*nk] functions which leads to the following transformed model in the three-phase coordinates.

$$L_{PF}\frac{di_{c1}}{dt} = -R_{PF}i_{c1} - d_{n1}v_{dc-}v_{CPF1} + \mathrm{v}_{\mathrm{s1}}$$
$$L_{PF}\frac{di_{c2}}{dt} = -R_{PF}i_{c2} - d_{n2}v_{dc-}v_{CPF2} + \mathrm{v}_{\mathrm{s2}}$$
$$L_{PF}\frac{di_{c3}}{dt} = -R_{PF}i_{c3} - d_{n3}v_{dc-}v_{CPF3} + \mathrm{v}_{\mathrm{s3}}$$

$$\mathrm{C_{dc}}\frac{\mathrm{dv_{dc}}}{\mathrm{dt}} + \frac{\mathrm{v_{dc}}}{\mathrm{R_{dc}}} = d_{n1}i_{c1} + d_{n2}i_{c2} + d_{n3}i_{c3} \quad (4)$$

The synchronous orthogonal frame is obtained from the general transformation matrix (4).

$$C_{dq}^{123} = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos\theta & \cos(\theta - {}^{2\pi}/_{3}) & \cos(\theta - {}^{4\pi}/_{3}) \\ \sin\theta & \sin(\theta - {}^{2\pi}/_{3}) & -\sin(\theta - {}^{4\pi}/_{3}) \end{bmatrix} (5)$$

Where $\theta = \omega t$ and the following equalities hold:

$$C_{123}^{dq} = (C_{dq}^{123})^{-1} = (C_{dq}^{123})^{T}$$

3. THYRISTOR CONTROLLED REACTOR.

Thyristor control reactor is usually a 3 phase assembly, normally connected in delta Arrangement to provide partial cancellation of harmonics. Often the main TCR reactor is split into two halves, with the thyristor valve connected between the two halves. This protects the vulnerable thyristor valve from damage due to flash over, lightning strikes, etc. $u_q T = \frac{di_{LTq}}{dt}$ (9)

TCR operates when the current varried from maximum to almost zero by varying the firing delay angle alpha (α). And alpha is defined as the delay angle from the point at which the voltage becomes positive to the point at which the thyristor valve is turned on and current starts flow.

3.1 MODELING OF TCR

The equations can be obtained by using Kirchhoff's voltage law.

$$v_{s1} = L_T\frac{di_{LT1}}{dt} + L_{PF}\frac{di_{c1}}{dt} + R_{PF}i_{c1} + d_{n1}v_{dc}$$
$$v_{s2} = L_T\frac{di_{LT2}}{dt} + L_{PF}\frac{di_{c2}}{dt} + R_{PF}i_{c2} + d_{n2}v_{dc}$$
$$v_{s3} = L_T\frac{di_{LT3}}{dt} + L_{PF}\frac{di_{c3}}{dt} + R_{PF}i_{c3} + d_{n3}v_{dc} \quad (6)$$

By applying Park's transformation,

$$L_T(\alpha)\frac{di_{LTd}}{dt} = L_T(\alpha)\omega iLT_q + L_{PF}\omega i_q - L_{PF}\frac{di_d}{dt} - R_{PF}i_d - d_{nd}v_{dc} + v_d$$
$$L_T(\alpha)\frac{di_{LTq}}{dt} = -L_T(\alpha)\omega iLT_d - L_{PF}\omega i_d - L_{PF}\frac{di_q}{dt} \mp R_{PF}i_q - d_{nq}v_{dc} + v_q \qquad (7)$$

The reactive part is taken to control the reactive current, *vq* = 0 and *Lf* (*α*) *ωiLTd* = 0

$$\frac{di_{LTd}}{dt} = B(\alpha)\omega\left[-L_{PF}\omega i_d - L_{PF}\frac{di_q}{dt} - R_{PF}i_q \quad - \quad d_{nq}v_{dc}\right] (8)$$

Where *B* (*α*) = 1/*LF* (*α*) *ω* is the susceptance. An equivalent input *u*qT is defined as Based on this expression, equation 1 becomes

$$B(\alpha) = \frac{u_q T}{\omega\left[-L_{pf}\,\omega i_q - L_{PF}\frac{di_q}{dt} - R_{PF}\,i_q - d_{nq}\,v_{dc}\right]} \quad (10)$$

The equivalent inductance is given by

$$L_{PF}(\alpha) = L_{PF}\frac{\pi}{2\pi - 2\alpha + \sin(2\alpha)} \quad (11)$$

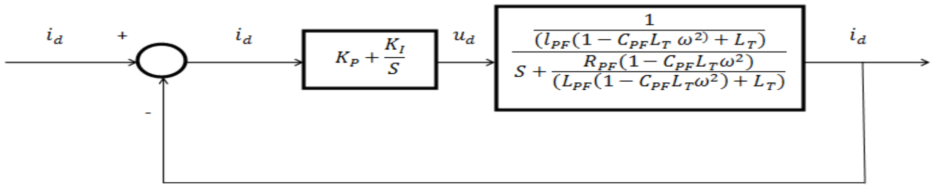
The susceptance is given by,

$$B(\alpha) = B\,\frac{2\pi - 2\alpha + \sin(2\alpha)}{\pi} \quad (12)$$ Where $B = 1/LPF\omega 0$.

4. P I controller.

The three phase supply currents ISA, ISB, ISC are measured and transformed into synchronous reference frame (d-q) axes rotating at the fundamental angular speed. Power p and q contain two components i.e. dc and ac. A dc components arising from the fundamental component of the source current, and an ac component due to its harmonic components. The ac components idh , iqh are extracted by two high pass filters and then, the harmonic component of the source current are obtained by applying the inverse transformation. To provide the inverter power losses and to maintain the DC voltage with in desired value, a dc component P Loss is added to the ac component of the imaginary power. It is generated by comparing the DC capacitor voltage with its reference value and applying the error to a P-I controller. To generate the required voltage command for the active filter inverter a d-q to a-b-c transformation is applied to convert the inverter voltage command back to the three phase quantities. The reference voltage of the active power filter is achieved by multiplying ac component of the source current in gain kh as *AF h sh v* = k i.*

4.1 Hormonic current control.



Inner control loop of the current i_d

Two kinds of loop one is fast inner current loop and another slow outer dc voltage control loop is adopted. The equations used for the modeling is written as shown below, because of the low coefficients the first and second derivative TCR capacitor voltages have no significant adverse impact on their performance of the proposed control technique.

With this transformation, the decoupled dynamics of the current tracking is obtained. The currents *id* and *iq* can be controlled independently. Furthermore, by using proportional integral compensation, a fast dynamic response and zero steady-state errors can be achieved. The expressions of the tracking controllers are

$$u_d = (L_{PF}(1 - C_{PF}L_T\omega^2) + L_T)\frac{di_d}{dt} + R_{PF}(1 - C_{PF}L_T\omega^2)i_d = k_p\tilde{i_d} + k_i\int \tilde{i_d}\,dt$$

$$u_q = (L_{PF}(1 - C_{PF}L_T\omega^2) + L_T)\frac{di_q}{dt} + R_{PF}(1 - C_{PF}L_T\omega^2)i_d = k_p\tilde{i_q} + k_i\int \tilde{i_q}\,dt \quad (13)$$

Where $\tilde{i}d = i^*d - id$ and $\tilde{i}q = i^*q - iq$ are current errors and i^*d and i^*q represents the reference signals of the *id* and *iq*, respectively.

The transfer function of the proportional–integral controllers can be given by

$$G_{i1}(s) = \frac{U_d(s)}{\tilde{i_d}(s)} = k_{p1} + \frac{k_{i1}}{s}$$

$$G_{i2}(s) = \frac{U_d(s)}{\tilde{i_q}(s)} = k_{p2} + \frac{k_{i2}}{s} \quad (14)$$

The current i_d of the inner control loop is as shown in figure. The current loops of the closed –loop transfer function are

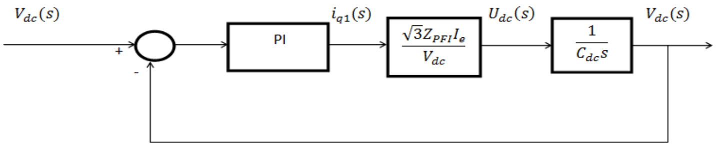
$$\frac{I_d(s)}{I_d^*(s)} = \frac{k_{p1}}{A}\,\frac{\left(s + \frac{k_{i1}}{k_{p1}}\right)}{s^2 + \left(\frac{B + k_{p1}}{A}\right)s + k_{i1}}$$

$$\frac{I_q(s)}{I_q^*(s)} = \frac{k_{p2}}{A}\,\frac{\left(s + \frac{k_{i2}}{k_{p2}}\right)}{s^2 + \left(\frac{B + k_{p2}}{A}\right)s + k_{i2}} \quad (15)$$

Where $A = LPF(1 - CPFLT\,\omega 2) + LT$ and $B = RPF(1 - CPFLT\,\omega 2)$.

The current closed-loop transfer functions can be given as,

$$\frac{I_d(s)}{I_d^*(s)} = 2\zeta\omega_{ni}\,\frac{s + \frac{\omega_{ni}}{2\zeta}}{s^2 + 2\zeta\omega_{ni}s + \omega_{ni}^2} \quad (16)$$



Compensated voltage regulated model

Where ωni =outer loop natural angular frequency ζ =damping factor. For the optimal value of the damping factor $\zeta=\sqrt{2}/2$, the theoretical overshoot is 20.79 %. The following design relations can be derived:

$kp_1 = kp_2 = 2\zeta\omega_{ni}\ (L_{PF}(1 - C_{PF}\omega^2) + L_T) - R_{PF}(1 - C_{PF}L_T\ \omega^2)$

$k_{i1} = k_{i2} = (L_{PF}\ (1 - C_{PF}\omega^2 L_T) + L_T)\omega_{ni}{}^2$

4.2 Bus Voltage Regulation

For the maintain of the dc bus voltage level at a desired value, it acts on *iq* to compensate the losses through the hybrid power filter components. The controller output is added to the *q*-component current reference iq . The equation 6 can be rewritten as,

$$C_{dc}\frac{dv_{dc}}{dt} + \frac{v_{dc}}{R_{dc}} = d_{nq}\ i_q \qquad (17)$$

Three phase filter currents can be given by

$$\begin{bmatrix} i_{c1} \\ i_{c2} \\ i_{c3} \end{bmatrix} = \sqrt{\left(\frac{2}{3}\right)} \begin{bmatrix} -\sin\theta \\ -\sin\left(\theta - \frac{2\pi}{3}\right) \\ -\sin\left(\theta - \frac{2\pi}{3}\right) \end{bmatrix} \qquad (18)$$

Fundamental rms value of filter current I_c is

$$I_c = \frac{i_q}{\sqrt{3}} \qquad (19)$$

Active filter voltage of q- axis (V_{mq}) is expressed as

$$V_{Mq} = q_{nq}V_{dc} = -Z_{PF1}i_{q1}^{*} \qquad (20)$$

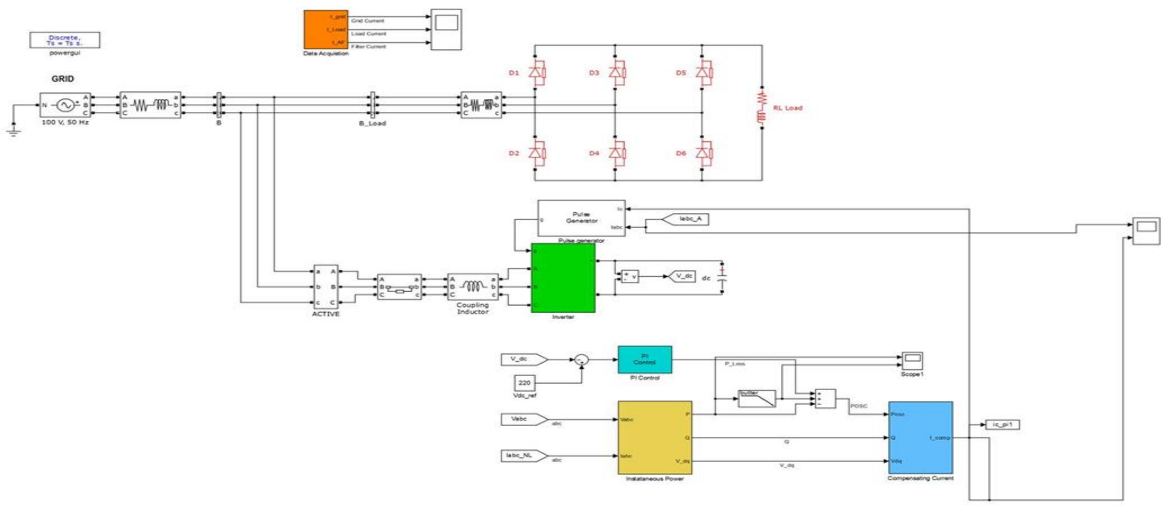
Where *Z*PF1 is the impedance of the passive filter at 50 Hz and *iq1**.*q*1 is a dc component. An equivalent input *u*dc can be written as

$$U_{dc} = q_{nq}\, i_q. \qquad (21)$$

The deduced control effort of the dc voltage loop.

$$i_q^{*} = \frac{v_{dc}}{-z_{PF1}i_q}u_{dc} \qquad (22)$$

Simulation in MAT lab simulink

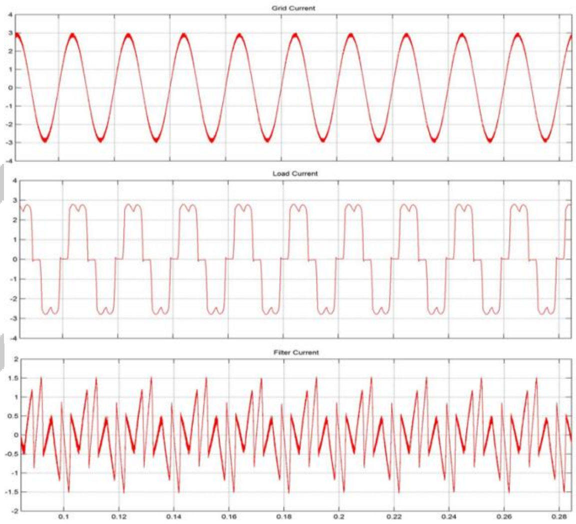


5. Simulation Results.

SPECIFICATION PARAMETERS

Line to Line source voltage, and frequency	$V_{s\text{-}L\text{-}L}$=208 V, f_s=60 Hz
Line impedance	L_s=0.5 mH, R_s=0.1 Ω
Non linear load	L_{L1}=10 mH, R_{L1}=27 Ω
Linear load	L_{L2}=20 mH, R_{L2}=27 Ω
Passive filter parameters	L_{pf}= 1.2 mH, C_{pf}=240 μF
Active filter parameters	C_{dc}=3000 μF , R_{dc}=1k Ω
DC bus voltage of APF of SHAF	V_{dc}=50 V
Switching frequency	1920 Hz
Inner controller parameters	K_{p1}= K_{p2}=43.38 ; K_{i1}= K_{i2}=37408
Outer controller parameters	K_1=0.26 ; K_2=42
Cut off frequency of the low pass filters	F_c=70 Hz
TCR inductance	L_T= 25 mH

5.1 Simulation waveforms



The combination of SHPF-TCR for harmonic elimination with a three phase harmonic produced load. The grid currenti_{s1}, the load currenti_{L1}, and the filter current (SHPF-TCR) i_{c1} are in phase with Voltage. The THD (total harmonic distortion) of a supply current is brought down from 26 % to 1.13 % .The combination of SHPF-TCR compensator gives a very good level of performance such that the supply current is close to sinusoidal and in phase with the supply voltage.

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