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Modeling of Active Power Filter for Correcting Power Factor in 3-Phase Systems of Variable Loads

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Abstract:
Due to the increase of demand in electric energy, the necessity of applying more attention to its quality is necessary. A variety of loads such as rectifier devices, power supplies and speed adjust drives such these loads cause high harmonic in drawn power.
In order to investigate the performance, it is required to model 3-phase system with variable loads. In this paper, a conventional proportional plus integral (PI) controller has been used to control this system.
To validate the mathematical model for a wide range of loads, two loads are considered with 3-phase AC source in the process of assessment. The first load is considered an unbalanced load. Each phase has a different independent type of load. The second load is a nonlinear load (rectifier load).
3-phase active power filters (APFs) are used to improve the power factor, which reduces the consumed apparently power; consequently, the overall performance will improve. A practical approach for implementing an APF has been presented in this work is a Voltage-source inverter-based shunt active power filter. This approach continuously requires one variable, which is the phase angle between the voltage and current to improve the performance of the system.

Keywords: Electric energy, rectifier devices, power supplies, (PI) controller.

الملخص:

نتيجة لزيادة الطلب على الطاقة الكهربائية، الحاجة للتركيز على جودتها امر ضروري. نظرا لوجود احمال متنوعة مثل اجهزة التقويم، مغذيات القدرة والمعدات الكهربائية ذات مدى سرعات واسع. هذه الاحمال تسبب في ظهور توافقيات في القدرة المسحوبة. تولد هذه التوافقيات العديد من المشاكل مثل تشوهات في مجال جهد المصدر، سخونة المعدات والاجهزة، أخطاء في انظمة الحماية وانظمة قراءة سريان الطاقة. كنتيجة لذلك، تنخفض كفاءة أنظمة القدرة.

للتخلص من هذه المشاكل، تم استخدام مصفيات القدرة لتحسين عامل القدرة. في هذه الورقة تم استخدام مصفي ثلاثي الطور للقدرة الفعالة (مصدر جهد مستمر وعاكس على التوازي). هذه الطريقة تحتاج باستمرار الى متغير واحد وهو زاوية الطور ما بين الجهد والتيار لتحسين الاداء للنظام. استخدم متحكم تناسبي مع تكاملي (IP) مع هذا المصفي. صمم هذا النموذج حتى يمكن استخدامه مع متحكمات مختلفة.

Introduction:

As it well known, the harmonics generate many problems such as distorted voltage waveform, equipment overheating, malfunction in system protection, and inaccurate power flow metering. They also reduce the efficiency of the generation system by drawing reactive current component from distribution network.

This frame of work is dedicated for the process of incorporating APF on-line with 3-phase power system. The Filter itself is 6 controlled electronic switches - two for each phase- IGBTs. All connected in parallel with a DC source. This filter injects the compensated current to maintain the voltage and current grid in phase.

The switches, at appropriate order, receive the firing signals from the PWM. The later receives the error signal from the controller. After sensing the line currents and transform the 3-phase system into the d-q system, the PI controller acts to eliminate the error between the total angle of grid voltage and its current for each phase.

Due to quickly switching at rectification process, the power factor is very low in power electronics equipment with highly harmonics, which causes very fast changes in reactive power [1], the same idea was proposed by [2].
Nevertheless, of its low cost and high performance, Passive filters have restrictions because of adding them in the network overlap with the system impedance, which leads to resonance with the actual loads [3]. Also in [4], they suggested to suppress the resonance by hysteresis control. A dynamics of a dc-link voltage is applied to achieve stability of SAPF using model reference control. That compensate the generated harmonics due to the load current [5].
In [6], the authors suggested applying linear control strategy for this type of filters. The approach was applying of Input-Output linearization on dq0 rotating reference frame. The performance showed improvement in power factor and maintain minimum harmonic load currents.
An optimal controller based on predictive control approach has introduced by [7]. The controller has been applied in the current control loop. The advantage was the independency of nonlinear control strategy from the on-line optimization. The reason was fast dynamics of current tracking, which ensures the stability of current loop and load's independency.
The authors have introduced a solid framework supported by experimental evidence in [8]. They implement a fuzzy logic controller to avoid some uncertainty in the modeling process.

System Modeling:

In the modeling procedure, it is assumed that loads are independent from the network loads. Unbalanced and nonlinear loads are considered later of simulation purposes. [1] The complete system is shown in; Figure 1, whereas represents the target subsystem for the modeling process (Source and Filter).

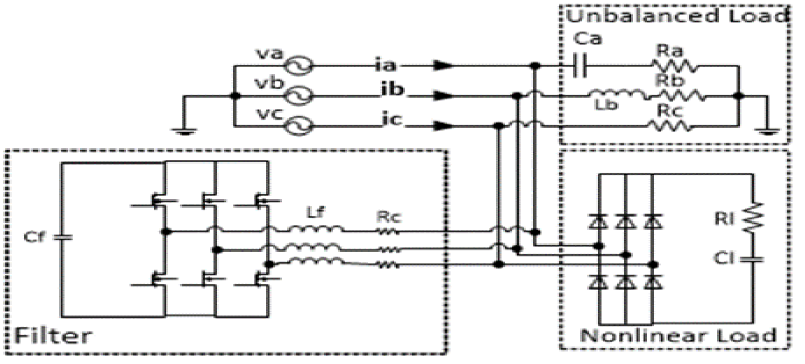

Figure 1: System Configuration

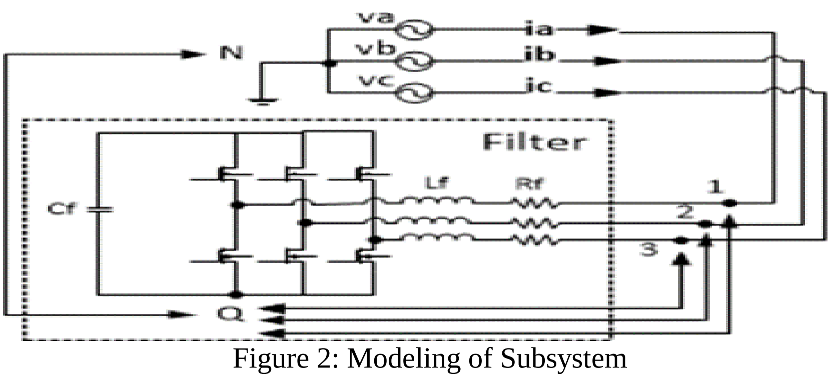

Figure 2: Modeling of Subsystem

To investigate the rate of change of currents and voltages between the supply and the filter, Kirchhoff laws for current and voltage are applied. For simplicity, we consider the inverter switches are ideal; therefore, we ignore the leakage currents and the drop voltages on each IGBT.

For each phase In Figure 2, we obtain a system as,

$$v_a = v_1 = L_f \frac{di_a}{dt} + R_f i_a + v_{aQ} + v_{QN}$$
$$v_b = v_2 = L_f \frac{di_b}{dt} + R_f i_b + v_{bQ} + v_{QN}$$
$$v_c = v_2 = L_f \frac{di_c}{dt} + R_f i_c + v_{cQ} + v_{QN} \quad (1)$$

Where v_{QN} the voltage is difference between point Q (reference of the filter) and the neutral of the source and is obtained by applying Kirchhoff ($v_a + v_b + v_c = 0$) and ($i_a + i_b + i_c = 0$) on the system equation in (1). These yields $v_{QN} = \left[-\frac{1}{3}\sum_{p\in\{a,b,c\}} v_{PQ}\right].v_{dc}$, where v_{dc} the voltage is across the capacitor Cf.
The timing function, which is controlled by 6 pulses comes from the PWM, must has the condition,

$$sw_a = \begin{cases} \mathbf{1}, & s_u = 1, s_l = \mathbf{0} \\ \mathbf{0}, & s_u = 0, s_l = \mathbf{1} \end{cases}$$

Where s_u & s_l represent the upper and lower switches for phase 'a' at the inverter side. It means for a particular phase v_a upper switch is on; the lower must have an opposite state.
The voltage at each phase is directly affected by this switching process as, $v_{aQ} = sw_a v_{dc}$
With this function, we can now substitute back into system (1) to obtain,

$$\begin{aligned} v_a &= L_f\frac{di_a}{dt} + R_f\, i_a + \left(sw_a - \frac{1}{3}\textstyle\sum_{i\in\{a,b,c\}} sw_i\right) v_{dc} \\ v_b &= L_f\frac{di_b}{dt} + R_f\, i_b + \left(sw_b - \frac{1}{3}\textstyle\sum_{i\in\{a,b,c\}} sw_i\right) v_{dc} \\ v_c &= L_f\frac{di_c}{dt} + R_f\, i_c + \left(sw_c - \frac{1}{3}\textstyle\sum_{i\in\{a,b,c\}} sw_i\right) v_{dc} \end{aligned} \quad (2)$$

Let $[(sw_a - \frac{1}{3}\sum_{i\in\{a,b,c\}} sw_i)\, v_{dc}]$ be a symbolic function SW_{ph}, which is the switching control function.

$$\begin{aligned} \frac{di_a}{dt} &= \frac{1}{L_f}(-R_f i_a - SW_{ph} + v_a) \\ \frac{di_b}{dt} &= \frac{1}{L_f}(-R_f i_b - SW_{ph} + v_b) \\ \frac{di_c}{dt} &= \frac{1}{L_f}(-R_f i_c - SW_{ph} + v_c) \end{aligned} \quad (3)$$

Due to the coupling of states, the model is a nonlinear. The resultant system is in abc-frame. It needs to be transferred into dq0-frame to apply the control approach.

Controller Design

In order to convert the state equations into the required transformation, we need to apply Park's transformation

$$u_{dq0} = K_s u_{abc} \rightarrow u_{abc} = K_s^{-1} u_{dq0}$$
$$i_{dq0} = K_s i_{abc} \rightarrow i_{abc} = K_s^{-1} i_{dq0}$$

K_s andK^{-1}_s are the transformation matrices. The resultant state in dq0- frame, is

$$\begin{bmatrix} \dot{i_d} \\ \dot{i_q} \end{bmatrix} = \begin{bmatrix} -R_f/L_f & \omega \\ -\omega & -R_f/L_f \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{1}{L_f} \begin{bmatrix} v_d \\ v_q \end{bmatrix} - \frac{1}{L_f} \begin{bmatrix} SW_d \\ SW_q \end{bmatrix} v_{dc} \quad (4)$$

The last system represents the augmented system for currents and voltage control.

The complete process of the transformation can be follow as in [9] and [10].

A. Current control loop

We start with the internal loop to control the currents id& iq. By rearranging system (4), we have,

$$\begin{aligned} L_f \, {}^{di_d}/_{dt} + R_f i_d &= L_f \omega i_q - SW_d v_{dc} + v_d \\ L_f \, {}^{di_q}/_{dt} + R_f i_q &= -L_f \omega i_d - SW_d v_{dc} + v_q \end{aligned} \quad (5)$$

Now let's define the comprehensive inputs for both d and q frames as

$$\begin{aligned} u_d &= L_f \omega i_q - SW_d v_{dc} + v_d \\ u_q &= -L_f \omega i_d - SW_q v_{dc} + v_q \end{aligned} \quad (6)$$

Through the switching functions, we can pick terms such that (6) becomes

$$u_d = k_{pi}\tilde{\imath}_d + k_{ii}\int \tilde{\imath}_d \ dt$$
$$u_q = k_{pi}\tilde{\imath}_q + k_{ii}\int \tilde{\imath}_q \ dt$$

For tracking the error of currents, we let:

$$\tilde{\imath}_d = i_d^* - i_d$$
$$\tilde{\imath}_q = i_q^* - i_q$$

Substituting back into system (4) and taking Laplace transform.

The open-loop current controller transfer function is:

$$G_{iol}(s) = \frac{U_d(s)}{\tilde{I}_d(s)} = \frac{U_q(s)}{\tilde{I}_q(s)} = k_{pi}\frac{s + k_{ii}/k_{pi}}{s}$$

It results a closed loop transfer function on the form:

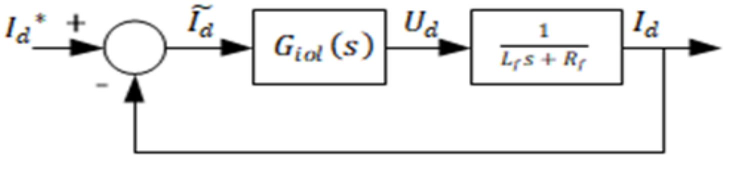

Figure 2: Figure 5: Current Control Loop

$$G_{icl}(s) = \frac{I_d(s)}{I_d^*(s)} = \frac{I_q(s)}{I_q^*(s)} = \frac{k_{pi}s + k_{ii}}{L_f s^2 + (k_{pi} + R_f)s + k_{ii}}$$

Where the characteristic equation of the closed loop system is

$$s^2 + \frac{(k_{pi}+R_f)}{L_f}s + \frac{k_{ii}}{L_f}=0 \qquad (7)$$

The general form of a characteristic equation of closed-loop transfer function of second order system is present in [11] and others as,

$$\Delta = s^2 + 2\zeta\omega_n s + {\omega_n}^2$$

It gives two roots of the form:

$$s_1, s_2 = -\zeta\omega_n \pm j\omega_n\sqrt{1-\zeta^2}$$

For stable performance, the damping factor $\zeta = \sqrt{2}/2$ and $\omega_n = 10 > 0$

By equating Equations (7) and (8), we obtain K_{pi} and K_{ii}.

$$\frac{(k_{pi}+R_f)}{L_f} = 2\zeta\omega_n \rightarrow k_{pi} = L_f(2\zeta\omega_n) - R_f$$

$$k_{ii}/L_f = {\omega_n}^2 \rightarrow k_{ii} = L_f({\omega_n}^2)$$

A. Voltage control loop:

The flow of power between the filter and source is consists of two parts active power $p = v_d i_d$ and reactive $q = -v_d i_q$ (no effect of vq at ideal situation). This keeps the vdc a maximum voltage across the dc link of the SAPF. By acting on the supply current, it can compensate the losses through the active power filter's resistive–inductive branches. Ideally, it must act on the direct current component id. From Figure2, we have the DC link side of the filter

$$C_f \frac{dv_{dc}}{dt} = SW_d i_d + SW_q i_q = u_{dc} \qquad (9)$$

We pick SW_d such that

$$u_{dc} = k_{pv}\tilde{v}_{dc} + k_{iv}\int \tilde{v}_{dc}\ dt, \qquad (10)$$

Where ($\tilde{v}_{dc} = v_{dc}^* - v_{dc}$) is the dc voltage tracking error.
The PI controller is

$$u_{dc} = kv_p\widetilde{v_d} + kv_i\int \widetilde{v_{dc}}\ dt$$

This gives a transfer function

$$G_{vol}(s) = \frac{U_{dc}(s)}{\tilde{v}_{dc}(s)} = k_{pv}\frac{s + k_{iv}/k_{pv}}{s} \qquad (11)$$

The overall closed-loop TF is:

$$\frac{v_{dc}(s)}{v_{dc}^{*}(s)} = 2\zeta\omega_{nv}\frac{s + \omega_{nv}/2\zeta}{s^2 + 2\zeta\omega_{nv}s + \omega_{nv}^2} \qquad (12)$$

This leads to controller gains $k_{pv} = 2\zeta\omega_{nv}v_{dc}$ and $k_{iv} = \omega_{nv}^2 v_{dc}$. Pick the ζ and ω_{nv} as in current loop controller.

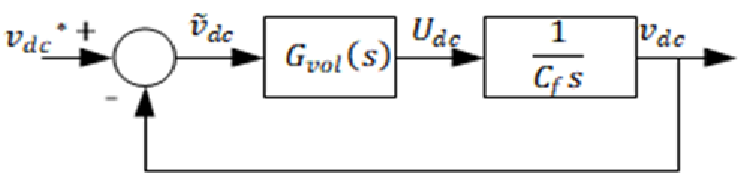

Figure 4: DC voltage Control Loop

Results and Discussion:

In this work, the objective loads include an unbalanced 3-phase and 3-phase Rectifier. The used parameters and constants are given in Table 1. The values that are shown here is not actual Data of a physical system; however, they are only for simulation purposes

Table 1: Table 1: Parameters of Simulation

Parameter	Symbol	Value	Unit
Source	Vabc	$220*\sqrt{2}$	Peak Volt
Frequency	f	50	Hz
Load 1 (Unbalanced)	Branch A: R / L Branch B: R / L Branch C: R	1.5 / 0.66 0.8 / 0.1 20	Ω / H Ω / H KΩ
Load 2 (Rectifier)	Rl Cl	1 200	KΩ F
Filter AC side	Rf Lf	1.3 2	Ω µH
Filter DC side	Cf	1600	µF

The simulation has been performed on MatLab/Simulink environment. First, the process of simulation started without applying the designed filter to present the system performance. In second stage, the filter has been linked to the grid and results have been recorded accordingly.

Figure 3 shows the performance of the network without including the Shunt Active Power Filter. It can be seen clearly that the currents are out phase form the source voltages due to the unbalanced load. In addition to the obvious distortion comes from the nonlinear load.

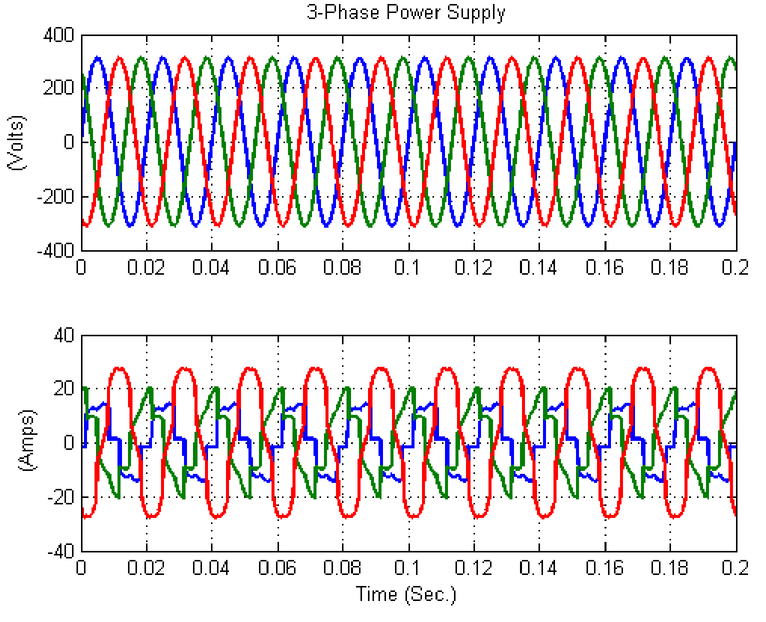

Figure 3: System Performance w/o SAPF

The currents drawn by the loads are shown in Figure 4. The upper part represents the unbalance load current. Each phase has its own impedance. Phase c is a pure resistive load. The lower part is the nonlinear load, represents the drawn current via rectification process. This load imposes a regulated distortion in the source waveform.

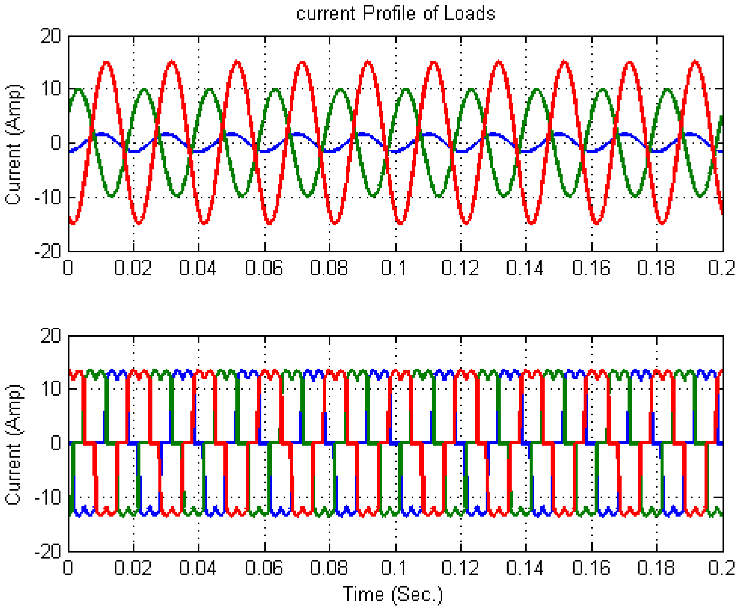

Figure 4: Load Current Profile

After connecting the SAPF, a major improvement has appeared on the shape of current waveform. The distortion almost is vanished. The phase currents have return back in phase with the supply voltage.

Figure 5 illustrates a noticeable increase in amount of drawn current; however, the degree of the grid synchronization between the voltage and current for each phase is evidence.
The behavior of the SAPF and waveform of the provided current is shown in Figure 6.
The peak value of compensated current is quite high which almost reached 40 Amps. This is manageable because there is an inverse proportional between the between the degree of synchronization and the filter parameters. Therefore, it is trade off. Whenever the filter resistance increases, the injected current decreases, the degradation in the performance happens.

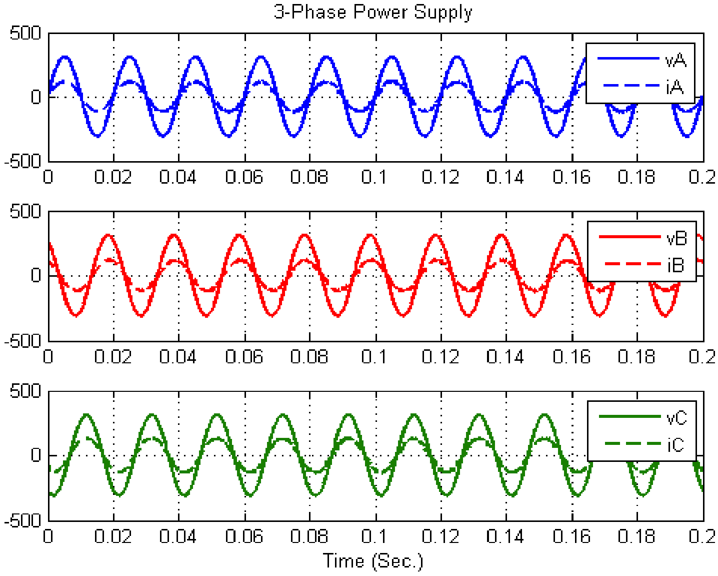

Figure 5: The System Performance with the SAPF

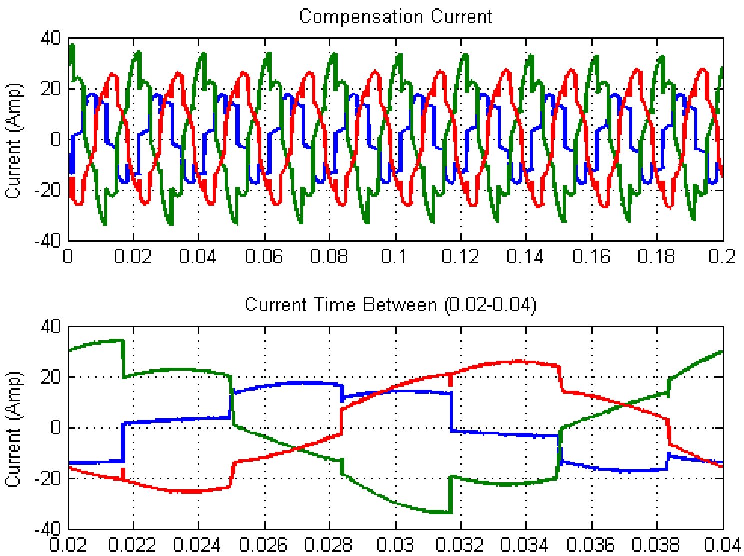

Figure 6: Compensation Current by the Filter

Conclusion:

In summary, the purpose of this work is to introduce a theoretical control scheme of power systems. A general method of modeling a shunt active power filter is presented. To prove an evidence of working model, a PI controller was derived to provide a PWM block with a suitable current reference to be injected into the grid to eliminate the harmonic caused by the wide range of loads.

The simulation results prove the control scheme was capable of suppressing the harmonics in the system in balanced sinusoidal shape. Not only was the unbalanced load current eliminated, but also, the distortion due to the effect of the nonlinear load.

A practical experiment could be implemented to compare the theoretical results with the empirical.

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