

A new method of STATCOM controlling for harmonic mitigation and power factor correction

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Abstract

This paper presents a control algorithm of 3ph STATic synchronous COMPensator (STATCOM). The algorithm depends on the accurate reference currents extraction from only the nonlinear load current spectrum in frequency domain using Fast Fourier Transfer (FFT). Then the determined harmonics and reactive components of load current are added together to form the compensating reference signals, the PI controllers then generate signals which control the Pulse Width Modulation (PWM) method. The simulation of the study is carried out under MATLAB/Simulink environment to show the usefulness of this control algorithm with nonlinear dynamic loads. It determines exactly the phase shift between the power system current and source voltage using only load current measurement. It is also able to calculate accurately the harmonics presence in source current. Various simulation results are presented with many modes of operation of dynamic nonlinear reactive loads. The results show a perfect damping of harmonics and reactive power compensating. The current Total Harmonic Distortion (THD) maintains the IEEE STD 519 Standard and power factor is almost 1, the STATCOM also has a fast dynamic response for transients.

Keywords: STATCOM, FFT, Power Factor correction, Harmonic mitigation, Harmonic extraction, THD, IEEE STD 519, controller, STATCOM control system.

Introduction

With the advancement in power electronic technology, these days various consumer and industrial loads in the power systems are nonlinear, such as Adjustable Speed Drives (ASD), arc furnaces, inverters, computers, fax machines, high power diode rectifiers etc. These nonlinear loads draw non-sinusoidal currents from utilities due to their operation thereby causing a poor power quality at the utility side. The harmonics are generated when nonlinear equipment draws current in short pulses. These harmonics in load current can sometimes result in overheated transformers and neutrals, blown fuses, tripped circuit breakers, increased losses in the lines, decreased power factor, and may cause resonance with the capacitors connected in parallel to the system (Dang et al., 2015; Fang et al., 2007; Fujita, 1996). Instruments can be affected similarly, giving erroneous data or otherwise performing unpredictably. The most serious of these are malfunctions in medical instruments. Consequently, many medical instruments are provided with line-conditioned power (IEEE Std 519, 1992).

In addition, most of the industrial loads draw reactive currents plus fundamental current, which could be lagging or leading the source voltage. This causes low levels of Power Factor. In such cases, load draws more current for the same useful power (Dang et al., 2015).

Problems can arise in case of large system interconnections, especially when the connecting AC links are weak (Nazrul et al., 2013). Reactive power compensation is an important issue in the control of electric power systems. Reactive power increases the transmission system losses and reduces the power transmission capability of the transmission lines. Moreover, reactive power flow through the transmission lines can cause large amplitude variations in the receiving-end voltage (Nazrul et al., 2013).

STATCOM is one of the most important Flexible AC Transmission System (FACTS) system. It has been used for power system stability, voltage regulation, reactive power compensating, harmonic filtering, etc. As a hardware, it consists of a controlled Voltage Source Inverter (VSI) or Voltage Source Converter (VSC) connected in parallel to the nonlinear load, dc capacitor and a controller. It is connected to the power system through a step-up transformer (Sreenivasarao et al., 2013; Ghadir et al., 2008; Zhengping, 2013). STATCOM compensates harmonics and reactive currents that are required by the load, so the load draws only a fundamental current from the grid. A STATCOM Controller, comprises of harmonic extraction, reactive current extraction and current regulation (Collins, 2005).

In (Xu et al., 2007) FFT was applied on both the measured source current and voltage to calculate active and reactive power in order to reduce current THD. In (Kumar, 2011; Car-

bone et al., 1995; Mayordomo et al., 1998; Madrigal et al., 2000). FFT analysis is used with harmonic domain to reduce voltage harmonics.

In this paper, a new algorithm of harmonic and reactive components extraction from the frequency spectrum of only the load current is used. The FFT analysis of the load current is used to determine the amplitude and shift of the existing harmonics h_n . It determines the reactive current phase and amplitude accurately using the FFT analysis for the determined current load only. This algorithm needs only load current measuring, which makes the control system simpler and decrease the complexity and cost. To make the STATCOM output match the extracted signal, PI controllers are used. Unlike SRF (Synchronous Reference Frame) or PQ theory which depends on transferring three phase load current and source voltage into $\alpha\beta$ or QD reference frame, and calculate active and reactive instantaneous power, i.e. a lot of calculating, measurements and wasted time, also they do not treat an unbalanced loads, in this new algorithm, each phase is treated alone, that means it is effective with unbalanced loads

The system was tested with several modes of operation for dynamic-reactive nonlinear load. The spectral performance shows that STATCOM brings the system into compliance with IEEE STD 519 Standard (IEEE Std 519, 1992; Hoevenaars et al., 2003) and power factor is almost 1.

System configuration

The proposed system is comprised of a STATCOM and a serial ac line smoothing reactance (L_c) installed in front of the target load.

The STATCOM and the nonlinear load are in parallel at the point of common coupling (PCC) as shown in Fig 1.

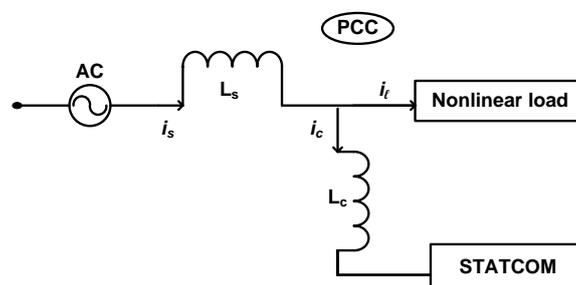


Figure 1. Proposed hybrid system, (Xu et al., 2007; Al-Zamil, 2001)

STATCOM

The three-phase STATCOM is based on the Voltage Source Inverter (VSI) topology. STATCOM consists of a six-switch VSI, inductance L_c and dc bus capacitor C (or dc capacitor voltage V_{dc}). The current that is supported by each switch is the maximum compensation inductor current (i_c). This current is easily determined through a simple model of the nonlinear load current (i_l). From Fig 1, the compensator current that is required to produce a sinusoidal line current (i_s) given by the power supported by the load. That is, the compensating inductor current is:

$$i_c = i_s - i_l \quad (1)$$

Where the line current supports the power consumed by the load and the compensator (Xu et al., 2007; Al-Zamil, 2001).

The voltage that should be supported by each switch is the maximum voltage that appears across the capacitor. The dc bus nominal voltage (V_{dc}) has to be greater than or equal to the line-line voltage peak in order to actively control i_c . There is a fundamental compromise in the selection of the compensation inductance L_c . The ability to track the desired source current improves as the compensation inductance is made smaller. As the inductor is made smaller, however, a higher switching frequency is required to keep the ripple in the line current acceptably small. A practical choice of L_c guarantees that the STATCOM can generate a current with a slope equal to the maximum slope of the load current. The upper bound on compensator inductance is (Xu et al., 2007; Al-Zamil, 2001; Rao et al., 2000; Singh et al., 2009):

$$L_c \leq \frac{\frac{2}{3}V_{dc} - V_{xn}}{\max \left| \frac{d i_{NLxn}}{dt} \right|} \quad (2)$$

where:

V_{xn} : the peak line-neutral voltage of phase x, i_{NLxn} : the peak line-neutral current of phase x.

The lower bound on inductor size is dictated by the acceptable level of switching frequency ripple current. The required capacitor size (C) is dictated by the maximum acceptable voltage ripple. A good initial guess of the value of C is (Al-Zamil, 2001):

$$C \geq \frac{\max(\int_0^t i_c \cdot dt)}{\Delta V_{C_{max}}} \quad (3)$$

where: $\Delta V_{C_{max}}$ is the maximum acceptable voltage ripple.

2.2. The nonlinear load

The nonlinear load is connected to the power system at the PCC. The representative nonlinear load used in this experiment is a 3ph, 6 pulses controlled thyristor rectifier as an industrial load, Fig 2. This load draws odd and even harmonics and reactive current. Note, we could use any other nonlinear load like arc furnaces, adjustable speed motor drives, diode rectifiers, etc.

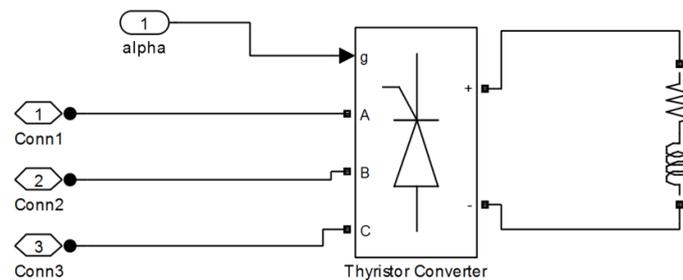


Figure 2. The nonlinear load, MATLAB-Simulink

Dynamic nonlinear load: The nonlinear load is dynamic and the delay angles α are changed during the simulation automatically, Fig 3. The values of $\alpha = \{0^\circ, 1^\circ, 2^\circ, \dots\}$, according to the load operating. The order of the harmonics that will be drawn by load is related to the values of α : if α is larger, then THD is larger. For every value of α there are new values of load current, the drawn harmonics, the reactive current and the source current.

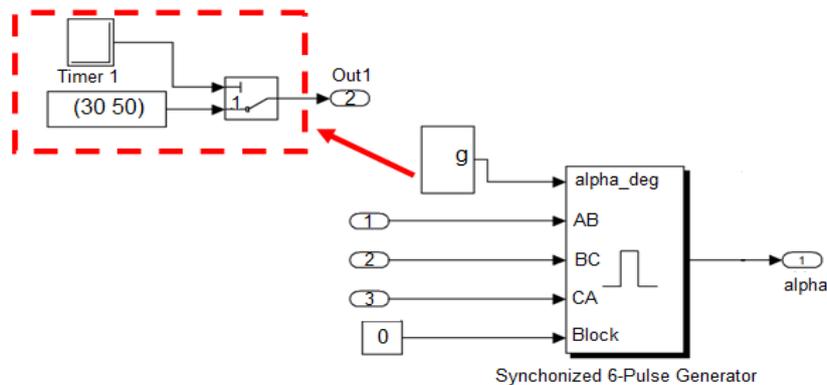


Figure 3. Circuit drive of dynamic nonlinear load, MATLAB-Simulink

Control algorithm of STATCOM

Harmonic extraction

The harmonic extraction is done using FFT (Carbone et al., 1995; Madrigal et al., 2000) analysis of the load current. Subsystems are created in MATLAB/Simulink to achieve Fourier transfers calculations.

Fig 4. shows the subsystem ,which is used in harmonic extraction, where A_n, B_n are Fourier constants; represent the amplitude and the phase of the harmonic n, C_n is the amplitude of harmonic n and φ_n is the phase shift of harmonic n.

First, the FFT is applied to calculate harmonics h_n , $n=2, 3, 4, \dots, 39$ in sequence to form the desired harmonic compensating signal as in the flow diagram in Fig 5(a).

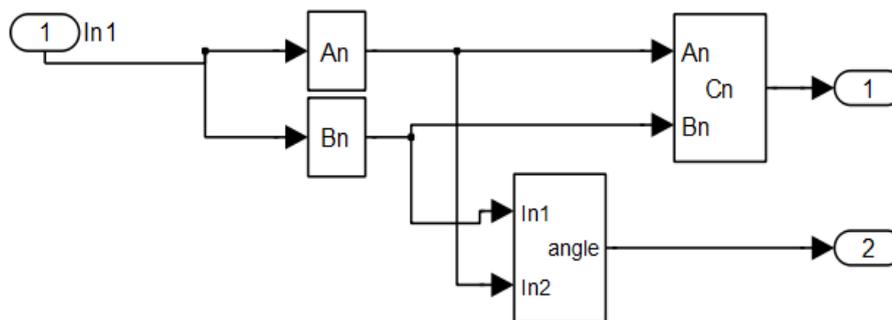


Figure 4. Total subsystem to calculate φ_n & C_n

Reactive current extraction

Applying the extraction algorithm that uses FFT on the load current for the harmonic 1 (i.e the fundamental component), which represents the reactive current that is drawn by the load. FFT determines the phase angle and amplitude of the fundamental load current to form the reactive current component. This reactive current causes a phase shifting between the source voltage and the current (i.e., low power factor (PF)). The control system then generates an equivalent current with opposite phase and amplitude. Finally, the extracted harmonic (φ_n, C_n) and the reactive signals are added together to form the compensating reference signal.

Current modulator controller

The compensating current is determined and subtracted from the reference signal for the three phases, and the results are the error signals. Error signals are passed to three PI controllers, which produce control signals that control PWM method to generate the desired pulses (Alex, 2013; Wang, 2001). The output pulses are then drive the transistors of the STATCOM inverter, Fig 5(b).

The gains of the PI controllers are found by trial and error method for best response for the test system considered in this paper.

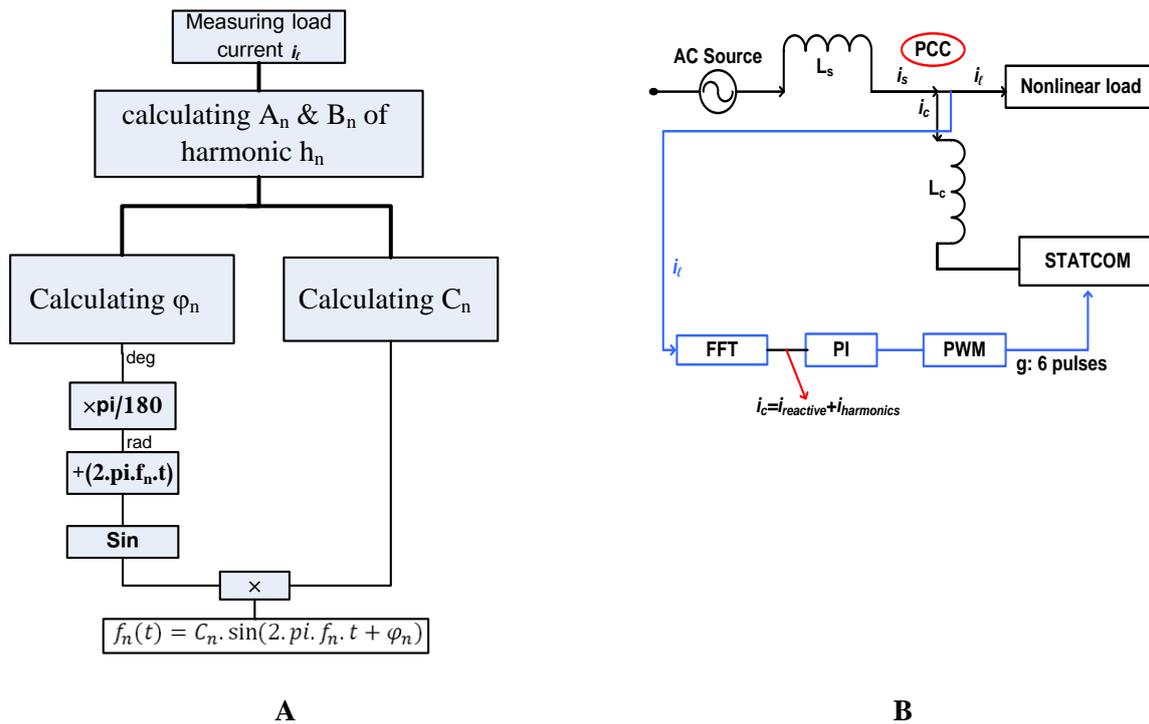


Figure 5. a) Flow diagram of the extraction algorithm, b) Controller block diagram

Simulation results and discussion

The proposed system is simulated in MATLAB/Simulink, Fig 6. The utility grid is 3ph, 400V, 50Hz.

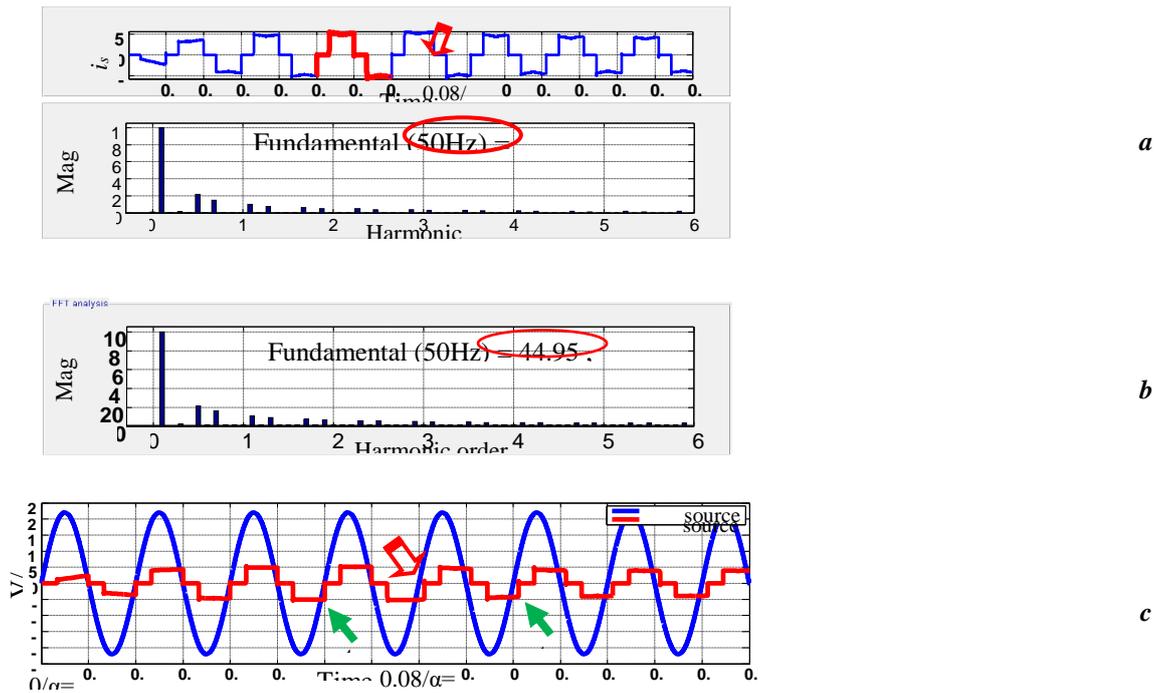


Figure 7. Source current without compensating, a) When $\alpha=30^\circ$, b) When $\alpha=50^\circ$, c) Source current and voltage

When $\alpha=30^\circ$ without compensating, the current was lagging with $\varphi_1=-0.52$ rad because the load drew some reactive current, and when $\alpha=50^\circ$ at $t=0.08$ sec, the load drew more reactive current which cause a larger shift angel $\varphi_2=-0.87$ rad, Fig 8(a). These values of φ lead to PF=0.86 when $\alpha=30^\circ$ and PF=0.64 when $\alpha=50^\circ$, Fig 8(b). We conclude that the big values of α cause low levels of PF and more power losses for the same amount of useful power. To determine the effect of α changes on the harmonics that are drawn by the load, we have measured THD% and it was 31% (>15; out the limit of IEEE STD 519 (Hoevenaars et al., 2003)) as in Fig 8(c). this means changing α caused big change in PF and negligible change in THD.

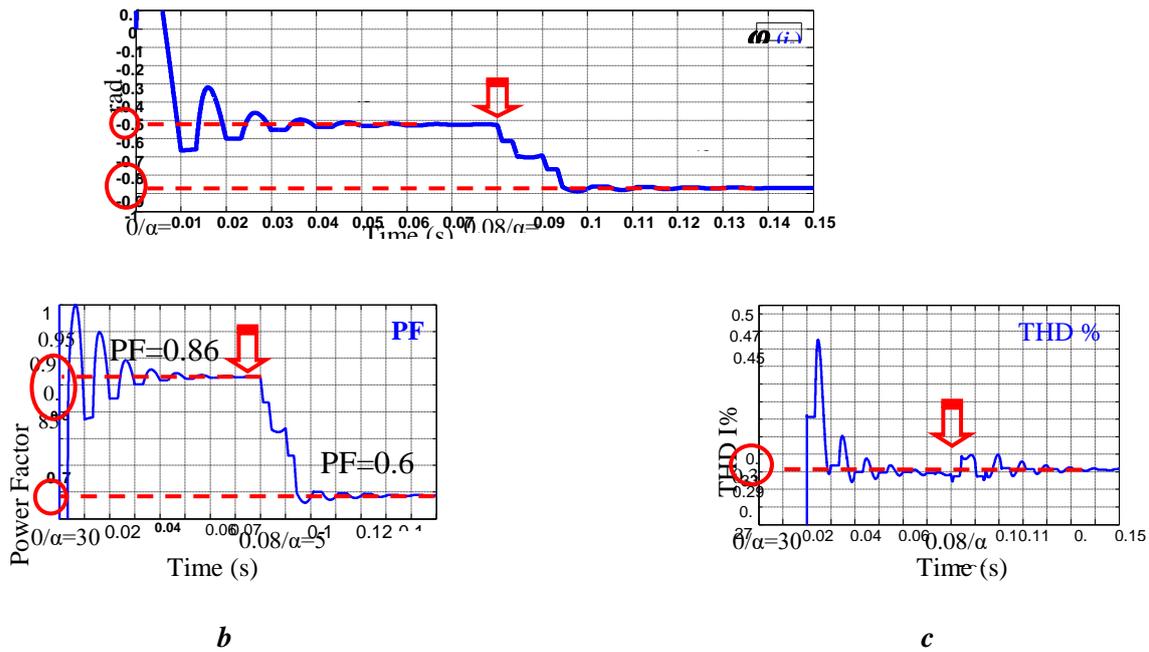


Figure 8. Phase shift φ , PF and THD before compensating, a) φ in radian, b) PF, c) THD%

STATCOM is turned on

In this case, STATCOM senses load current and this creates the compensating signals in order to form the desired compensating current. At the beginning, the load drew harmonics when $\alpha=30^\circ$ before the STATCOM stapling which cause a big value of THD=33.22% (>15; out the limit of IEEE STD 519 (Hoevenaars et al., 2003)), Fig 9(a). After 0.02 sec, STATCOM stabled and damped the load harmonics, which decreased THD to 6.22% (<15; in the limit of IEEE STD 519), Fig 9(b).

At $t=0.08$ sec α was changed to 50° . This caused more drawing of harmonics by load and an increasing in THD to 23.13% (>15; out the limit of IEEE STD 519) before the STATCOM stapling, Fig 10(a). At $t=0.1$ sec STATCOM was stable and it has damped load harmonics and decreased THD to 9.96% (<15; in the limit of IEEE STD 519), Fig 10(b).

Note, source current is almost sinusoidal after compensating. When the load changed, STATCOM compensated again the new harmonics and reactive currents and THD didn't rise to the same level when STATCOM was off. THD_i matched the IEEE STD 519 limits when stabling with the two values of α , Fig 10(c). Note, the designed STATCOM damped all harmonics existed in source current till the 39th.



Figure 9. Source current and its THD when $\alpha=30^\circ$, a) Before stapling, b) After stapling

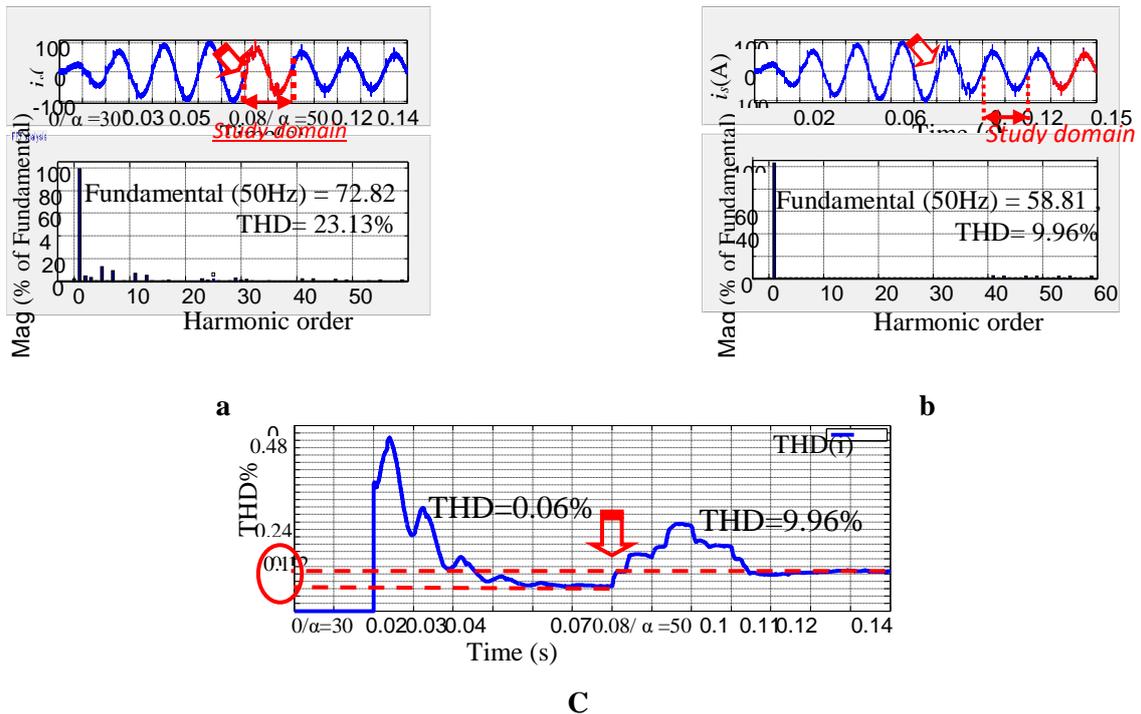


Figure 10. Source current and its THD% when $\alpha=50^\circ$, a) Before compensating, b) After compensating, c) THD%

Fig 11, shows the source current and voltage when STATCOM is running and the load is changing. In t_1 STATCOM was on and $\alpha=30^\circ$. Note that there was a shift angle φ because the load drew reactive current before STATCOM was stabled. In t_2 STATCOM was stabled and compensated the reactive load and $\varphi_1 \approx -0.01$ rad, Fig 12(a), and the equivalent PF was 0.99995, Fig 12(b).

Back to Fig 11, in $t_3=0.08$ sec, α has become 50° before STATCOM was stabled and the shift angle was φ , in $t_4=0.1$ sec, STATCOM was stabled in less than one cycle after the load was changed ($t_s \leq 0.02$ sec) and compensated the determined reactive load which decreased φ_2 to 0.01 rad, Fig 12(a) and PF to 0.99995 again, Fig 12(b); that means, STATCOM generated

the required reactive current which changed with every value of α and shifted the source current to be in phase with the source voltage, which maximize PF \approx 0.99995.

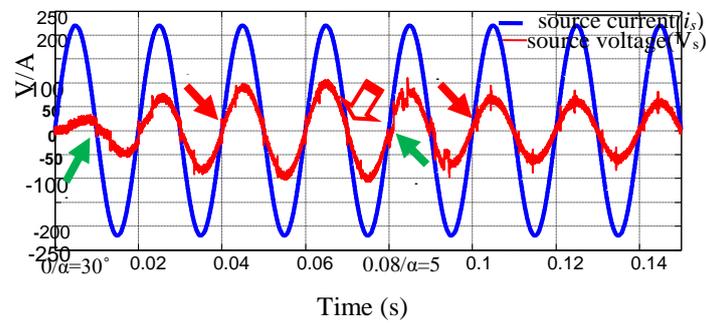


Figure 11. Source current and voltages when the STATCOM running

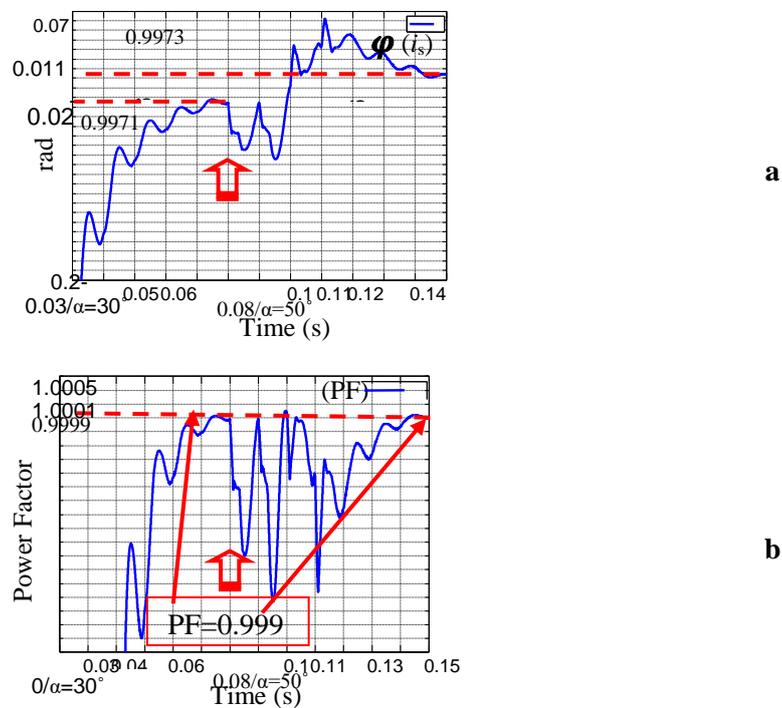


Figure 12. ϕ and PF after stapling and compensating, a) ϕ in radian, b) PF

The values of THD and PF for all values of α are presented on table 1, before and after compensating. Our results were similar to (Shiney et al., 2013) and they were under the limits of IEEE STD 519 (Hoevenaars et al., 2003).

Table 1. THD and PF before and after filtering for the chosen α

α°	statues	THD%	<or >	SCR	φ rad	PF
0	Before filtering	29.45	>	12		
	After filtering	3.41	<	12		
30	Before filtering	32.46	>	15	-0.52	0.86
	After filtering	6.22	<	15	-0.01	0.99995
40	Before filtering	39.99	>	15		
	After filtering	11.74	<	15		
50	Before filtering	33.37	>	15	-0.87	0.64
	After filtering	9.96	<	15	0.01	0.99995

THD: the total harmonic distortion of the current.

SCR: short circuit rate and given as $\frac{I_{SC}}{I_L}$, I_{SC} is maximum short-circuit current at PCC, I_L is maximum demand load current (fundamental frequency component) at PCC.

STATCOM maintains THD in the limits of IEEE STD 519 and $PF \approx 1$ as shown in table 1 for the two values of α .

In (Al-Zamil et al., 2001), the author used PQ theory to extract reference signals, and tested the system with a nonlinear, which is similar to the load in our study. PQ theory needs both load current and voltage measurement and Clark and Bark transformers, ie. more calculating and time, and this theory does not treat an unbalanced loads .

Fig 13 shows the results comparing with (Al-Zamil et al., 2001). THD values in our study is smaller than THD values in (Al-Zamil et al., 2001) for all tested values of α ($\alpha=20^\circ, 30^\circ, 40^\circ$). In (Al-Zamil et al., 2001), PF is 0.966 but $PF=0.99995$ in this study.

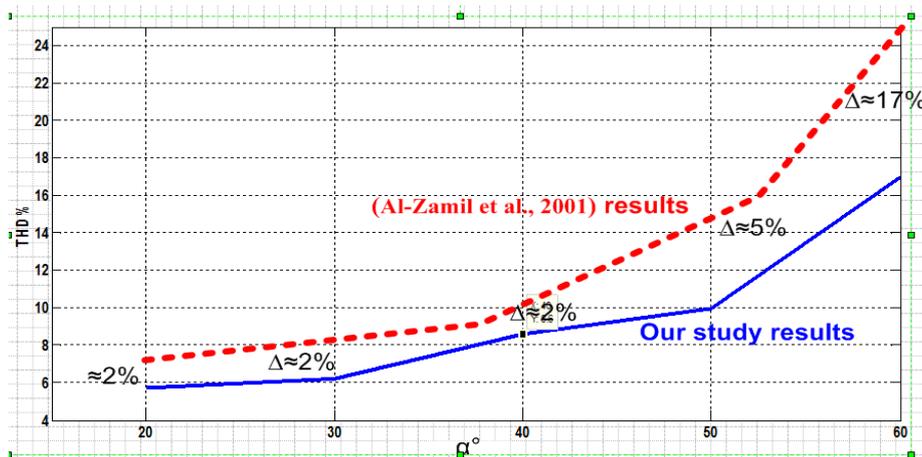


Figure 13. Comparing with (Al-Zamil et al., 2001).

In (Kumar, 2011), the author used SRF theory to extract reference signals, and tested the system with a three phase rectifier. THD was 6.24% for Kumar, 2011, where THD=4.81% in our study for the same load. SRF theory depends on transferring three phase currents and voltages into $\alpha\beta$ reference frame, this needs a lot of calculating and time, and this theory did not treat an unbalanced loads.

In (Xu, Y et al., 2007), the author used FFT to extract reference signals using source current and voltage. THD was 18.8% for (Xu et al., 2007), where in our study, THD=3.14% for the same load.

Fig 14(a) shows (Adarsh et al., 2015) results, where the author used PQ theory to extract references for adaptive PWM controller. The system was tested with three phase rectifier and THD was 6.10%, where THD=4.96% in our study for the same load, Fig 14(b).

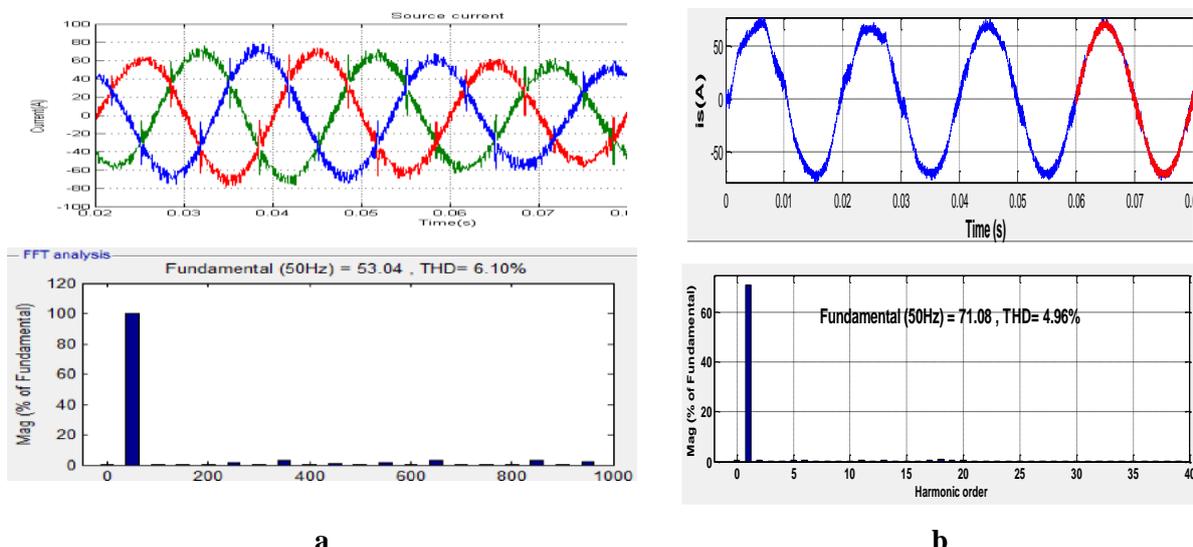


Figure 14. Comparing with (Adarsh et al., 2015), a) (Adarsh et al., 2015) results, b) our results.

We have tested the designed STATCOM with $\alpha=60^\circ$ and found that higher order harmonics (≥ 60) appeared, Fig 15, and we have concluded that the limit of our system is $\alpha=60^\circ$ because THD=16.98% (>15 ; out of limits of IEEE STD519). When we added subsystems that extract harmonics higher than 60, the simulation was stopped and sent an error message "out of memory", so we considered that $n=60$ is the limit of our system.

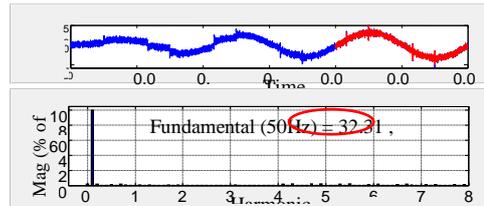
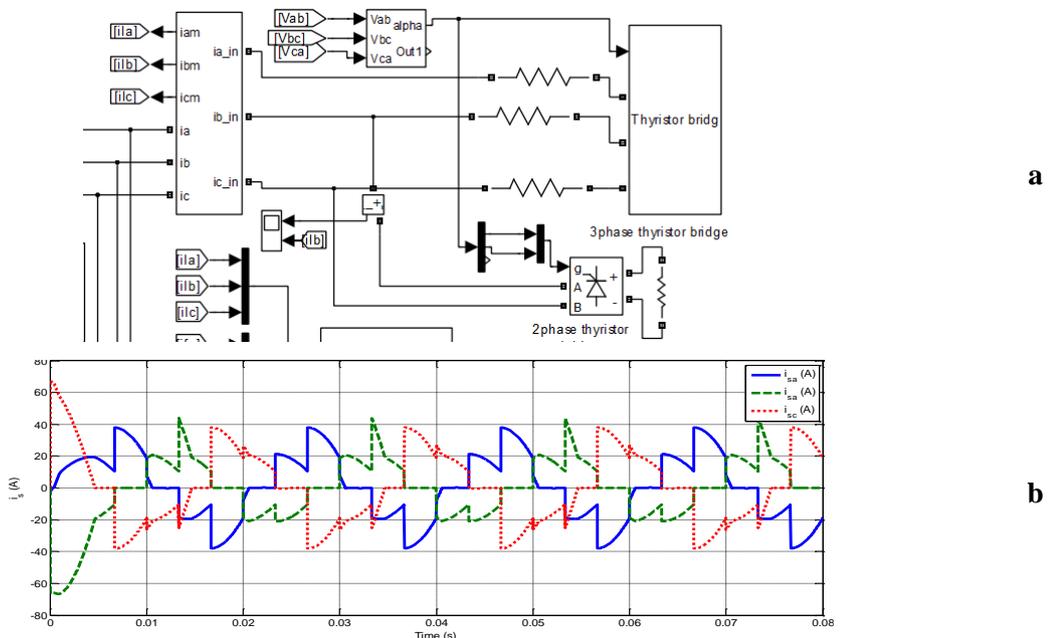
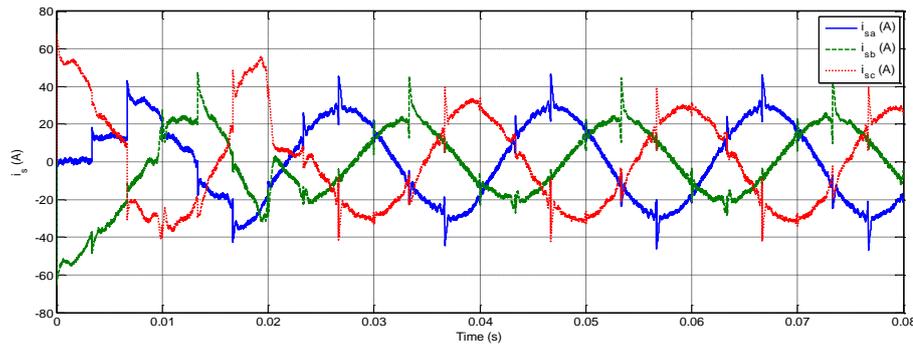


Figure 15. Source current and its THD% when $\alpha=60^\circ$

We tested the system with unbalanced nonlinear load, Fig 16(a). Fig 16(b). shows the disturbed unbalanced source current before compensating, where in Fig 16(c), the current is balanced and was filtered.





c

Figure 16. Source current for unbalanced load , a) before compensating, b) after compensating.

The values of current THD before and after compensating are presented on table 2. THD, after compensating, is under the limits of IEEE STD 519 for the three phases.

Table 2. THD before and after compensating for unbalanced nonlinear load.

source current	status	THD%
i_{sa}	Before filtering	40.47
	After filtering	11.48
i_{sb}	Before filtering	40.35
	After filtering	13.75
i_{sc}	Before filtering	43.08
	After filtering	12.82

Conclusions

The algorithm, which uses FFT to extract harmonic existed in load current, is used to damp harmonics till 39th. Extracting harmonics using FFT leads to accurate results in damping all harmonics existed in source current. STATCOM with the designed extracting algorithm compensates all harmonics drawn by static and dynamic nonlinear loads. The control system using this algorithm is an instantaneous response for sudden changes in dynamic load current. Controlling STATCOM with this algorithm needs only load current measuring. The designed STATCOM is able to compensate harmonics and reactive power for the unbalanced nonlinear loads because it treats every phase alone, since traditional STATCOMs treat all phases together, which may cause increase in the distortion and disturbing in one of the phases. The designed STATCOM has compensated the reactive power drawn by the reactive nonlinear load and $PF \approx 1$. High order harmonics are usually negligible when considering THD, but they

cause an added reactive power absorbing, which means they should be considered in power factor correction.

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طريقة جديدة للتحكم ب STATCOM من أجل تخفيض التوافقيات وتصحيح عامل

الاستطاعة

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الملخص

يقدم هذا البحث خوارزمية تحكم بمعوض تزامني ستاتيكي ثلاثي الطور *STATIC synchronous COMPensator* (STATCOM). تعتمد الخوارزمية على الاستخراج الدقيق للتيارات المرجعية من الطيف التوافقي لتيار الحمل اللاخطي فقط في المجال الترددي باستخدام تحويل فوريير السريع *Fast Fourier Transfer (FFT)*. ثم يتم جمع قيم مركبات التوافقيات والتيار الردي المستخرجة معاً لتشكيل الإشارات المرجعية، ثم تقوم المتحكمات التناسبية التكاملية بتشكيل إشارات التحكم التي تقود دائرة تعديل عرض النبضة. تم إجراء النمذجة في بيئة الماتلاب، وبيّنت النتائج فوائد خوارزمية التحكم هذه، واختبر النموذج المصمم مع أحمال لاخطية رديّة ديناميكية، وتم تحديد زاوية إزاحة الطور بين تيار الشبكة وجهده بشكل دقيق جداً بالاعتماد على القيم المقاسة لتيار الحمل فقط، كما أن هذه الطريقة قادرة على التحديد الدقيق للتوافقيات الموجودة في تيار الشبكة، وتم عرض نتائج النمذجة في أنماط مختلفة لعمل الأحمال اللاخطية الرديّة الديناميكية، بيّنت النتائج التخفيض الجيد للتوافقيات والتعويض الجيد للاستطاعة الرديّة، وتم تخفيض قيمة عامل التشوه التوافقي الكلي للتيار *Total Harmonic Distortion (THD)* لتصبح ضمن حدود المعيار الأمريكي العالمي *IEEE STD519*، وقيمة عامل الاستطاعة أصبحت تقريباً مساوية للوحد، وكان للمعوض *STATCOM* استجابة ديناميكية سريعة للحالات العابرة.

الكلمات المفتاحية: المعوض الستاتيكي التزامني، تحويل فوريير، تخفيض التوافقيات، استخراج التوافقيات، عامل التشوه التوافقي الكلي، المعيار الأمريكي *IEEE STD 519*، المتحكم، نظام التحكم.