Improve Power Quality Using Static Synchronous Compensator with Fuzzy Logic Controller

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Abstract — This paper presents the result of the simulation of synchronous static compensator (STATCOM) with fuzzy logic controller on a three phase power system. The behavior of this system in order to compensate the reactive power and harmonics will be described. The fuzzy logic controller does not require a mathematical model of the system and this is a big advantage to use this controller instead of conventional PI controllers. Furthermore, designing and implementation of this controller on the cheap microcontroller is easier than the conventional PI controllers. In this method, the compensation method is based on sensing the line current only an approach different from conventional methods, which require harmonics or reactive volt-ampere requirement of the load. PWM pattern generation is based on carrier less hysteresis based current control to obtain the switching signals. At the end, the result of simulation with MATLB Simulink software has been presented.

I. INTRODUCTION

In the recent years, the application of power electronics has been developed in Industry. Power electronic systems have non-linear behavior. Increasing these non-linear specifications leads to undesired Increment, from current harmonics and reactive power in AC lines to poor power factor and overall weakness of performance. These factors also leave an impression on other power consumers in a power network. To solve these issues, the STATCOMs (Static Compensators) are developed. In the recent years, the parallel current STATCOMs using PWM method have been widely used and developed as a reliable method to compensate the mentioned issues [1].

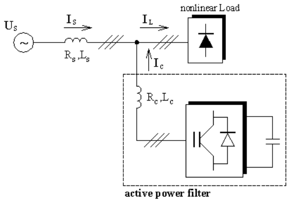
Duke, Round have proposed a scheme in which the required compensation current is calculated using a synthetic sinusoid generated technique by sensing the load current. In future, by sensing only the line current, this method is modified which makes this method implement easily [2].

However, the conventional PI controller was used for generating a reference current template, but the PI current needs an exact linear mathematics equation that is hard to implement. Recently, fuzzy logic controllers (FLCS) have generated a good application in Industry. Being more robust and easy to design is one of the advantages of these controllers over PI controllers. Also, they do not need an accurate mathematical model, and can continue with imprecise inputs and are able to work well in non-linear conditions

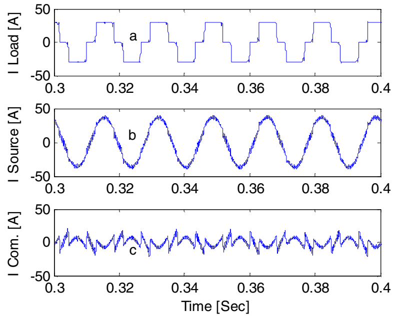
In this paper, a static compensator with FLC is simulated to compensate current harmonics and reactive power of non-linear load current. The control scheme is based on sensing only line currents; an approach which is different from convention ones that were based on sensing harmonics and reactive voltage amps requirements of the non-linear load. The three phase currents/voltages are detected from only two current voltage sensors. The voltage of DC capacitor is regulated to estimate the reference current template.

II. PRIMARY COMPENSATION PRINCIPLE

Fig 1.a shows the basic compensation principle. It has been controlled to draw/supply a compensation current (I_C) from/to the AC line and this leads to cancel current harmonics on the AC side. Fig 1.b shows different curves, curve A is the load current. Curve B is the desired main current and curve C shows the compensation current injected by a static compensator. To make main current sinusoidal, this wave includes all harmonics [3].



(a) Basic compensation principle



(b) Shapes of load, source and desired filter current waveforms

Figure 1. Static synchronous compensator

A. *Current Supplied by Source*

From Fig. 1.a, the real time current can be written as:

$$i_s(t) = i_L(t) - i_c(t) \tag{1}$$

and the source voltage is given by:

$$v_s(t) = V_m \sin \omega t \tag{2}$$

If non-linear is attached, the load current will have a fundamental and harmonic component that can be described with:

$$\begin{aligned} i_L(t) &= \sum_{n=1}^{\infty} I_n \sin(n\omega t + \phi_n) \\ &= I_1 \sin(\omega t + \phi_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n) \end{aligned} \tag{3}$$

The instant load power can be given as:

$$\begin{aligned} p_L(t) &= v_s(t) * i_L(t) = p_f(t) + p_r(t) + p_h(t) \\ &= V_m I_1 \sin^2 \omega t * \cos\phi_1 \\ &\quad + V_m I_1 \sin\omega t * \cos\omega t * \sin\phi_1 \\ &\quad + V_m \sin\omega t * \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n) \end{aligned} \tag{4}$$

According to (4), the fundamental power drawn by the load is:

$$p_f(t) = V_m I_1 \sin^2 \omega t * \cos\phi_1 = v_s(t) * i_s(t) \tag{5}$$

From (6), the source current after compensation is:

$$I_s(t) = p_f(t) / v_s(t) = I_1 \cos\phi_1 \sin\omega t = I_{sm} \sin\omega t \tag{6}$$

The peak current that the source must supply can be given as:

$$I_{sp} = I_{sm} + I_{sl} \tag{7}$$

If the static compensator compensates both of reactive power and harmonics, then $I_S(t)$ must be in the same phase with the voltage of static compensator. The compensated current can be given by:

$$i_c(t) = i_L(t) - i_s(t) \tag{8}$$

Hence, to have accurate and instantaneous compensation of reactive and harmonic power, it is necessary to estimate $i_S(t)$.

B. Estimation of the Reference Source Current

The peak value of reference current I_{sp} can be estimated by controlling the DC side Capacitor Voltage. Ideal compensation needs a sinusoidal reference current and needs to be in the same phase with voltage source. The source current after compensation is:

$$\begin{cases} i_{sa}* = I_{sp} \sin\omega t \\ i_{sb}* = I_{sp} \sin(\omega t - 120^\circ) \\ i_{sc}* = I_{sp} \sin(\omega t + 120^\circ) \end{cases} \tag{9}$$

In above equation, $Isp=I1\cos\Phi1+IsL$ is the amplitude of desired source current. So, the phase angle is calculated from the source voltage. Thus, the wave form and the phase of current source are calculated and only the amplitude of current source must be calculated. The peak value of reference current has been estimated by regulating the DC side capacitor voltage of the PWM converter. This capacitor voltage is compared with the reference value and the error is preceded in a fuzzy controller. The output of fuzzy controller has been considered as amplitude of the desired source current and the reference current is calculated by multiplying this peak value with a unit size vector in a phase with source voltage.

C. Role of DC Side Capacitor

The DC side capacitor serves two main purposes: It maintains a DC voltage with small ripple in steady state, and it serves as an energy storage element to supply a real power difference between load and source during the transient period. In the steady state, the real power supplied by the source should be equal to the real power demand of the load plus a small power to compensate the losses in the static compensator. Thus the DC capacitor voltage can be maintained at a reference value. However, when the load condition changes the real power balance between the mains and the load will be disturbed. This real power difference is to be compensated by the DC capacitor. This changes the DC capacitor voltage away from the reference voltage. In order to keep satisfactory operation or the static compensator, the peak value of the reference current must be adjusted to proportionally change the real power drawn from the source. This real power charged/discharged by the capacitor compensates the real power consumed by the local. If the DC capacitor voltage is recovered and attains the reference voltage, the real power supplied by the source is supposed to be equal to that consumed by the load again. Thus in this method, the peak value or the reference source current can be obtained by regulating the average voltage of the DC capacitor. A smaller DC capacitor voltage than the reference voltage means that the real power supplied by the source is not enough to supply the load demand. Therefore, the source current needs to be increased, while a larger DC capacitor voltage than the reference voltage tries to decrease the reference source current. This change in capacitor voltage has been verified from the simulation results.

III. DESIGNING POWER CIRCUIT OF A STATCOM

Required parameters for designing are as follows: L_n STATCOM Inductance and C_{dc} Dc side capacitance size.

A. L_C and $V_{dc\text{-}ref}$

Designing of these parameters is based on the following assumptions: Sinusoidal AC source voltage, to design L_C, the ac line current distortion must be limited to 5% and Fixed capability of reactive power compensation. PMW converter works in linear modulation mode according to the base of compensator rules, I_C needs to be generated to compensate the reactive power of the system. If the compensator compensates all the fundamental reactive power of the load, I_S will be emplaced and I_C should be orthogonal to V_S as shown in Fig 2. The source reactive power is calculated with the following equation:

$$Q_{c1} = 3V_s I_{c1} = 3V_s \frac{V_{c1}}{\omega L_c}(1 - \frac{V_s}{V_{c1}}) \tag{10}$$

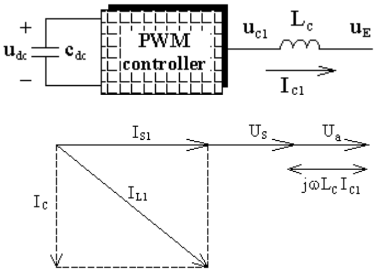


Figure 2: Vector diagram representing reactive power flow

The compensator inductor L_C, is also used to filter ripple of the converter current and hence, designing of L_C is based on the principle of harmonic current reduction. The ripple current of PWM converter can be given in terms of the maximum harmonic voltages which accurse at the $m_f\omega$ voltage.

$$I_{ch}(m_f\omega)=\frac{v_{ch}(m_f\omega)}{m_f\omega L_c} \tag{11}$$

In above equation, m_f is the modulation frequency.

B. DC Side Capacitor Design (C_{dc})

The capacitor size is determined with the peak to peak voltage and nominal AC link current with this equation:

$$C_{dc}=\frac{\pi * I_{cl,rated}}{\sqrt{3}\omega V_{dr,p-p(max)}} \tag{12}$$

For a 5KVA compensation capacity and a peak to peak 100v and a 50Hz system, the following parameters have been used: L_C=0.66mH, $V_{dc\text{-}ref}$=220V, C_{dc}=2000μF. Table I shows the compensator performance. For the selected values of different inductances, It is clear that by reducing the filter inductor to an optimum value, the compensator performance can be improved.

TABLE I
SYSTEM PERFORMANCE

L_{Cr} mH	% THD (of 10th cycle)	P.F.
0.4	2.26	0.9997
0.66	1.42	0.9999
1.0	1.51	0.9999
2	4.02	0.9992

IV. PURPOSED FUZZY LOGIC CONTROLLER

In order to implement a close loop controller of static compensator, first, the voltage of DC capacitor measured and then, the error ($e=V_{dc,ref}-V_{dc,act}$) calculated and use as a input for fuzzy logic controller. The output of fuzzy logic controller is used as a reference current after passing through a limiter.

The PWM converter switching signals are obtained by comparing the actual source currents with the reference current templates in the hysteresis current controller.

A. Base of Fuzzy Controller

In a fuzzy logic controller, the control action is determined from the valuation of a set of simple linguistic rules. The development of the rules requires a thorough understanding of the process to be controlled, but it does not require a mathematical model of the system. The schema of fuzzy logic controller presented in Fig.3.

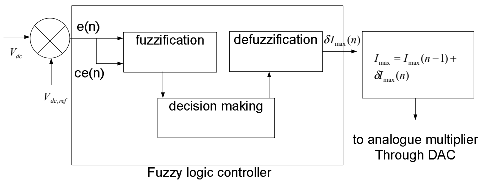


Figure 3: Fuzzy logic controller

The error e and change of error ce are used as numerical variables from the real system. To convert these numerical variables into linguistic variables, the following seven fuzzy levels or sets are chosen [4]: Seven fizzy sets for each input and output, Triangular membership functions for simplicity, Fuzzification using continuous universe of discourse, Implication using Mamdani's 'min' operator and Defuzzification using the 'height' method. Fig.4 shows the normalized triangular membership function used in Fuzzification.

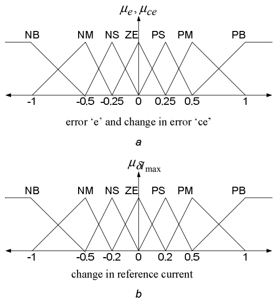


Figure 4: Normalized triangular membership function used in Fuzzification a) Membership functions for e and ce, b) Membership functions for $\eta\delta I_{max}$

B. Design of Control Rules

The design of fuzzy controller rules involves defining rules that relate the input variables to output. Also FLC does not depend on mathematical model but the design is mainly based on feeling and experiencing of the process. A new methodology for rule based design is based on the general dynamic behavior of the process [5]. The time step response of a stable closed loop system has a shape as shown in Fig. 5a

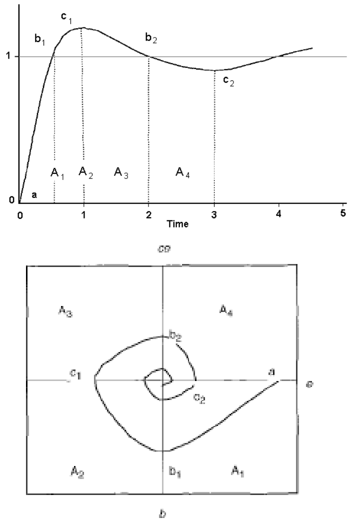


Figure 5: The step response a) Response of stable closed loop system b) Phase plane trajectory of step response

The input variables of FLC are the error e and the change of error ce. The time response has been divided into four regions A1, A2, A3, A4, and two sets of points cross-over (b1, b2) and peak (cl, c2). The index used for identifying the response area is defined as:

$$\begin{aligned} &A_1: \text{if} \quad e>0 \,\&\, ce<0, \quad A_2: \text{if} \quad e<0 \,\&\, ce<0 \\ &A_3: \text{if} \quad e<0 \,\&\, ce>0, \quad A_4: \text{if} \quad e>0 \,\&\, ce>0 \end{aligned} \tag{13}$$

The cross over index:

$$\begin{aligned} &b_1: e>0 \text{ to } e<0, ce<0 \\ &b_2: e<0 \text{ to } e>0, ce>0 \end{aligned} \tag{14}$$

and the peak valley index:

$$c_1: ce=0\,, e<0, \text{and } c2: ce=0, e>0 \tag{15}$$

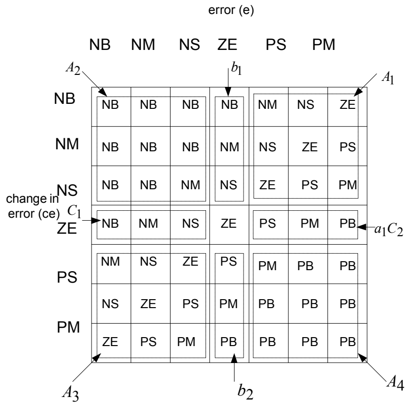
According to these four area, two sets of points and phase plane trajectory of e and ce, the rule base is framed. The corresponding rule for the region 1 can be formulated as rule R1 and has the effect of shortening the rise time:

If e is +Vc and ce is –Ve then SImax is –Ve

Rule 2 for region 2 decreases the overshoot of the system response, which can be written as:

If e is – ve and ce is – Ve then SImax is –Ve and other rules has been presented in Table 3.

TABLE II
CONTROL RULE TABLE



	NB	NM	NS	ZE	PS	PM	
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
	ZE	PS	PM	PB	PB	PB	PB

V. MODELING AND SIMULATION

The above system, include one three phase source voltage, PWM converter, nonlinear load and one controller. All parts modeled separately and then integrated to simulate the overall system.

A three-phase diode rectifier with R-L load is considered as a nonlinear load. The effect of source inductance is also considered. Due to the presence of source inductance, six overlapping and six lion-overlapping conduction intervals occur in a cycle. The dynamic equations during non-overlap and overlap intervals are given in (11) and (12), respectively:

$$p i_d = (V_O - (2R_s + R_L) i_d - 2v_d)/(2L_s + L) \tag{16}$$

$$p i_d = (V_O - (1.5R_s + R_L) i_d - 2v_d)/(1.5L_s + L) \tag{17}$$

Where Rs, Ls are the are the elements of the source impedance, Vd is a voltage that through from diode, Rl, Ll are the load parameters and id is the load current flowing through the diode pairs. Vo is the AC side line voltage segment.

The PWM converter has been modeled as a three phase AC voltage applied through filter impedance (R_c, L_c) on its input, and a DC bus capacitor on its output [6]. The three phase voltages V_{ca}, V_{cb} and V_{cc} reflected on the input side can be expressed in terms of the DC bus capacitor voltage V_{dc} and switching functions stating the on/off status of the devices of each leg T_A, T_B, T_C as:

$$\begin{aligned} v_{ca} &= \frac{V_{dc}}{3}(2T_A - T_B - T_C) \\ v_{cb} &= \frac{V_{dc}}{3}(-T_A + 2T_B - T_C) \\ v_{cc} &= \frac{V_{dc}}{3}(-T_A - T_B + 2T_C) \end{aligned} \tag{18}$$

The three-phase current flowing through the RL filter is:

$$\begin{aligned} p i_{ca} &= (\frac{1}{L_c})(R_c i_{ca} + (v_{sa} - v_{ca}) \\ p i_{cb} &= (\frac{1}{L_c})(R_c i_{cb} + (v_{sb} - v_{cb}) \\ p i_{cc} &= (\frac{1}{L_c})(R_c i_{cc} - (v_{sc} - v_{cc}) \end{aligned} \tag{19}$$

Also The DC current, calculated as follow:

$$i_{dc} = i_{ca} T_A + i_{cb} T_B + i_{cc} T_C \tag{20}$$

In the above equation, Vdc is equal to:

$$p V_{dc} = (\frac{1}{C_{dc}})(i_{ca} T_A + i_{cb} T_B + i_{cc} T_C) \tag{21}$$

The peak value of the reference current is estimated using controller by controlling the DC capacitor voltage in a close loop. The output of the control algorithm is the change in reference current .The peak reference current at the nth sampling time is determined by adding the pervious reference current.

$$I_{max}(n) = I_{max}(n-1) + \delta I_{max}(n) \tag{22}$$

The current hysteresis control, create the firing signals for PWM converter, if $i_{si} > i_s^* + hb$, the upper switch of the ith leg is off and if $i_{si} > i_s^* + hb$ the lower switch is on, where hb is a hysteresis band.

VI. SIMULATION RESULTS

Figs. 6-13 presents the simulation result of the mentioned static compensator with fuzzy logic controller. Fig. 6 shows the status of load, source and compensator currents after applying the compensator in the 0.485 second. Load current shown in Fig. 6a. Fig. 6b shows the current of AC source and Fig. 6c shows the output current of the compensator. As shown in Fig. 6b, the AC source current becomes sinusoidal from a stepped wave shape after applying compensator. Fig. 7 shows the detail of load, source and compensator current for one phase. As shown in Fig. 7 this wave forms becomes sinusoidal from a stepped shape and also the switching time is important here, in the other hand, the applying time of shunt static compensator is very important and has a relationship with the maximum capacity of the AC system. Fig. 8 shows the load current before applying static compensator. As shown in this figure, the wave form is non-sinusoidal and the effects of switching activity are visible. The THD in this situation is equal to 28%. Fig. 9 shows the compensated load current in any phase. As shown in this figure the wave form becomes sinusoidal and the effect of switching activity of nonlinear load removed. In this situation the THD is equal to 8% and as shown, decrease more than 20% in same condition. Fig. 10 shows the injected current in to the AC line with static compensator, this wave form is created base on the comparison of load current and the reference current, and then the PWM switching wave creates using fuzzy logic controller. Fig. 11 shows the voltage changes of DC capacitor. The overshoot is related to the time of applying the compensator. Fig. 12 shows the current of DC capacitor that change to non-sinusoidal after applying the compensator due to generation of required compensation current.

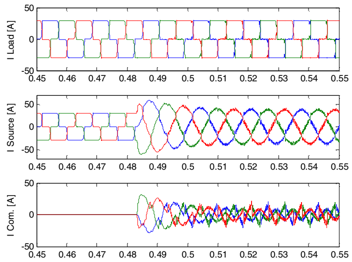


Figure 6. Status of load, source and compensator currents before/after applying the compensator

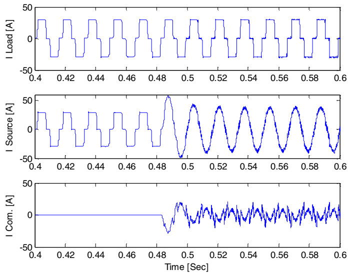


Figure 7. One Phase current status of system

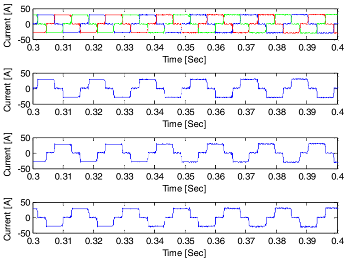


Figure 8. Load current before applying static compensator

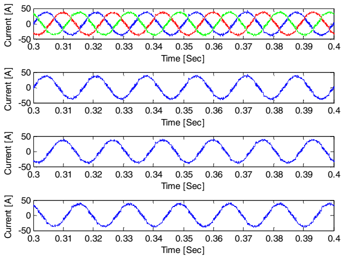


Figure 9. Compensated load current in any phase

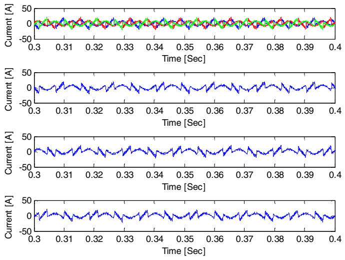


Figure 10. Injected current in to the AC line with static compensator

Fig.13 shows the changes of active and reactive power during the simulation. As shown in this figure, the active power becomes stable after running the simulation, and the reactive power is limited in a little band. This matter shows the exact operation of static compensator.

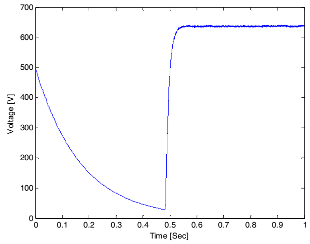


Figure 11: voltage changes of DC capacitor

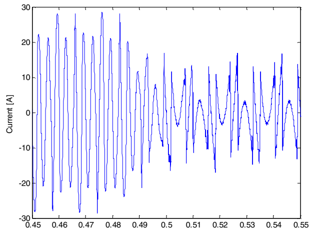


Figure 12: current of DC capacitor

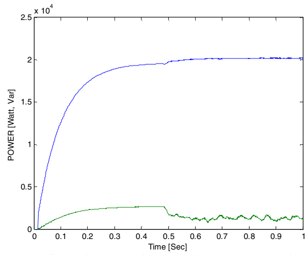


Figure 13: changes of active and reactive power during the simulation

VII. CONCLUSION

The static compensator with fuzzy logic controller is a good choice for solving the problem of power quality in the power system with harmonics and nonlinear load. In this paper the results of using fuzzy controller instead of conventional PI controllers presented. In this manner the fuzzy logic controller shows the good operation during the transient condition. The THD is limited to 8% that match with the IEEE-519 standard. Using the renewable energize like as solar energy instead of DC capacitor suggested to reduce the effects of losses and power usage in DC side for future researches.

REFERENCES

[1] L.A. Morgan, J.W. Dlxon, R.R. Wallace, “A three phase active power filter operating with fixed switching frequency for reactive power and current harmonic compensation", *IEEE Trans. on pow. elec.*, Vol.42, No.4, pp.402-408, 1995.

[2] R.M. Duke, S.D. Round, "steady state performance of a controlled current active Filter”, *IEEE Trans. on pow, elec,*, Vol.8, pp.140 146, 1993.

[3] R. Mienski, R. Pawelek, I. Wasiak, “Application of STATCOM controller-s for power quality improvement-modeling and simulation”, *IEEE/HQPC*, 2002.

[4] A.H.M.A. Rahim, E.P. Nowicki, and J.M. Bakhashwain1, “Fuzzy STATCOM Control Strategies for Power System Stabilization”, ACSE Jou., Vol.6, No.2, June 2006.

[5] B. Cao, T.-F. Li, C.Y. Zhang, “A research on fuzzy control method used in STATCOM”, Fuzzy Info. and Eng., Vol.2, pp. 1119–1129. 2009.

[6] L.O. Mak, Y.X. Ni, C.M. Shen, “ STATCOM with fuzzy controllers for interconnected power systems”, Elec. Pow. Sys. Res., Vol.55, pp.87–95, 2000.