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Performance Analysis of Statcom Compensator Using Adaline Based Control Techniques for Load Compensation

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***Abstract*: Power quality in the grid system reactive power compensation plays a vital role and also makes the power factor improvement. The STATCOM (Static Synchronous Compensator) is a shunt device interconnected to the grid system with large non-linear loads. The utilization of power electronic devices in the load the systems THD reduces with the increase in the consumption of reactive power. The performance of the STATCOM depends on the control algorithm i.e. the extraction of the current components. In this project STATCOM is controlled by IRP and SRF theory for compensation of reactive power and unbalance and these methods are compared with a new Adaline based algorithm. An Adaline based control technique consists of an on-line identified system model and a Pole-Shift (PS) feedback controller. An Adaline based control technique has resulted inconsiderable improved performance of STATCOM.**

***Keywords*— STATCOM, ADALINE Network, Adaptive PS Controller,Control algorithms, MATLAB.**

I. INTRODUCTION

Now-a-days power systems have become very complex with interconnected long distance transmission lines[1]. The interconnected grids tend to become unstable as the heavy loads vary dynamically in their magnitude and phase angle and hence power factor. Commissioning new transmission systems are extremely expensive and take considerable amount of time to build up[8]. Therefore, in order to meet increasing power demands, utilities must rely on power export/import arrangements through the existing transmission systems. The capacitor banks are used to improve power factor but having a number of disadvantages [3]. For power quality in the grid system reactive power compensation plays a vital role and also makes the power factor improvement. The FACTS devices offer a fast and reliable control over the transmission parameters, i.e. Voltage, line impedance, and phase angle between the sending end voltage and receiving end voltage[4]. The FACTS (Flexible AC Transmission Systems) devices, such as STATCOM has been introduced more recently which employs a VSC with a fixed DC link capacitor as a static replacement of the synchronous condenser. The utilization of power electronic devices in the load the systems THD reduces with the increase in the consumption of reactive power[7].

The performance of the STATCOM depends on the control algorithm i.e. the extraction of the current components. In this paper we will discuss about,instantaneous reactive power (IRP) theory, synchronous reference frame (SRF) theory and compared with the new algorithm ADALINE based on neural network.

II. MODELING OF THE STATCOM AND ANALYSIS

A. Operating principle

As is well known, the STATCOM is, in principle, a static (power electronic) replacement of the age-old synchronous condenser. Fig.1 shows the schematic diagram of the STATCOM [2].

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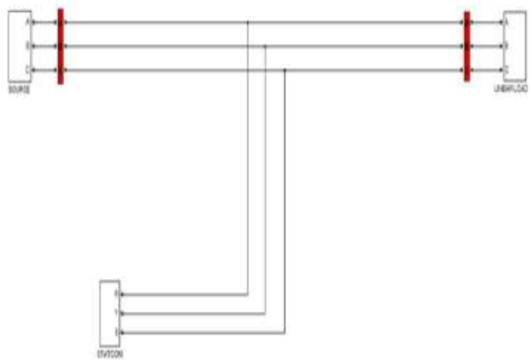

Fig.1:schematic diagram of statcom

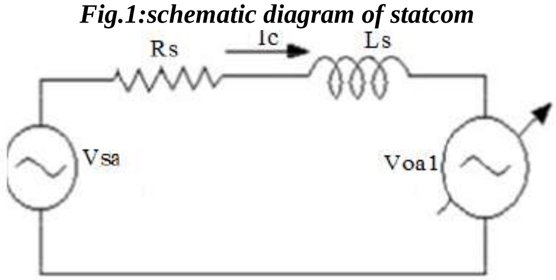

Fig.2: Per-phase fundamental equivalent circuit.

The per-phase fundamental equivalent circuit is as shown in fig.2.shows the source voltage, load and coupling inductor of the STATCOM with neglecting the harmonic content. If the fundamental component of the output voltage of the STATCOM is in-phase with the supply voltage then the current flowing out or towards the STATCOM is always 90 lagging or leading to the supply voltage. The STATCOM can also operate, when terminal voltage (fundamental) of the STATCOM is greater than the supply and lagging (and then current will lead the supply voltage). The STATCOM will then operate in fully capacitive mode supplying reactive power of the system. In case STATCOM current lags the system voltage, the STATCOM will operate in inductive mode injecting reactive VARs into the system [7].

B. Modelling

The modeling is carried out with the following assumptions:
1) All switches are ideal
2) The source voltages are balanced
3) Rs represents the converter losses and Ls represents losses of the coupling inductor.
4) The harmonic contents caused by switching action are negligible.

The 3-phase stationary *abc* coordinate vectors with apart from each other are converted into □ □ □-2-phase stationary coordinates (which are in quadrature). The □ axis is aligned with *a* axis and leading □ □ axis and both converted into *dq* two-phase rotating coordinates. The Park's *abc* to *dq* transformation matrix is equation (1)

$$k = \sqrt{\frac{2}{3}}\begin{bmatrix} Cos(\omega t) & cos(\omega t - 2\pi/3) & Cos(\omega t + 2\pi/3) \\ sin(\omega t) & sin(\omega t - 2\pi/3) & sin(\omega t + 2\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}$$

The actual proposed circuit is too complex to analyze as a whole, so that it is partitioned into several basic sub-circuits, as shown in Fig.1. The 3-phase system voltage, lagging with the phase angle α to the STATCOM output voltage υoabc differential form of the STATCOM currents are defined in (2) and (3).

$$v_{s,abc}= \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}}\, v_s \begin{bmatrix} sin(\omega t - \alpha) \\ sin\left(\omega t - \alpha - \frac{2\pi}{3}\right) \\ sin\left(\omega t - \alpha + \frac{2\pi}{3}\right) \end{bmatrix} \qquad (2)$$

$$L_s \frac{d}{dt}(i_{c,abc}) = -R_c i_{c,abc} + v_{s,abc} - \upsilon_{oabc} \qquad (3)$$

$$\upsilon_{0,qd_0} = m[0\ 1\ 0]^T\, \upsilon_{dc} \qquad (7)$$

where, υs,□ □,Rs and Ls have their usual connotations. The above voltages and currents are transformed into *dq* frame,

$$L_s \frac{d}{dt}(i_{cq}) = -R_c i_{cq} - wL_s i_{cd} + V_{sq} - V_{oq} \qquad (4a)$$

$$L_s \frac{d}{dt}(i_{cq}) = -R_c i_{cq} - wL_s i_{cd} + V_{sq} - V_{oq} \qquad (4b)$$

The switching function *S* of the STATCOM can be defined as follows

$$S=\begin{bmatrix}Sa\\Sb\\Sc\end{bmatrix}=\sqrt{\frac{2}{3}}m\begin{bmatrix}Sin(\omega t)\\Sin\left(\omega t-\frac{2\pi}{3}\right)\\Sin\left(\omega t+\frac{2\pi}{3}\right)\end{bmatrix} \quad (5)$$

$$MI=\frac{v0,peak}{Vdc}=\sqrt{\frac{2}{3}} \quad (6)$$

The STATCOM output voltages in *dq* transformation are

$$v_{0},qd_{0}=m[0\ 1\ 0]^{T}\ v_{dc} \quad (7)$$

$$i_{dc}=m\,[0\ 1\ 0][icq\ \ icd\ ico]^{T} \quad (8)$$

$$\frac{dv\ dc}{dt}=\frac{m}{C}\,i_{cd} \quad (9)$$

$$\frac{d}{dt}\begin{bmatrix}icq\\icd\\vcd\end{bmatrix}=\begin{bmatrix}\frac{Rs}{Ls}&-w&0\\w&-\frac{Rs}{Ls}&-\frac{m}{Ls}\end{bmatrix}\begin{bmatrix}icq\\icd\\vcd\end{bmatrix}+\frac{Vs}{Ls}\begin{bmatrix}-sin\alpha\\Cos\alpha\\0\end{bmatrix}$$
(10)

III. CONTROL ALGORITHMS

The performance of the STATCOM depends on the control algorithm i.e. the extraction of the current components. For this purpose there are many control schemes which are reported in the literature and some of these are instantaneous reactive power , synchronous reference frame (SRF) theory, computation based on per phase basis, and scheme based on neural network. Among these control schemes instantaneous reactive power theory and synchronous rotating reference frame are most widely used.

A. Instantaneous Reactive Power Theory

Instantaneous reactive power theory has been initially proposed by Akagi in 1983 The theory is based on the transformation of three phase quantities to two phase quantities in α –β frame and calculation of instantaneous active and reactive power in this frame[7].

Instantaneous P-Q Theory

The p-q theory uses a -b - 0 transformations and various definitions of active and reactive powers. The transformation of 3-Phase quantities (a-b-c) of stationary reference frame into 2-Phase quantities (a -b - 0) stationary reference frame is achieved by applying Clark's transformation and the calculation of instantaneous active and reactive power in this frame. ea, eb and ec, iLa, iLb and iLc are fed to the controller, and these quantities are processed to generate reference currents. The switching signals for the STATCOM is generated by comparing source current and reference current

$$\begin{bmatrix}v_0\\v_\alpha\\v_\beta\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{pmatrix}\frac{1}{\sqrt{2}}&\frac{1}{\sqrt{2}}&\frac{1}{\sqrt{2}}\\1&-\frac{1}{2}&-\frac{1}{2}\\0&\frac{\sqrt{3}}{2}&-\frac{\sqrt{3}}{2}\end{pmatrix}\begin{bmatrix}v_a\\v_b\\v_c\end{bmatrix} \quad (11)$$

$$\begin{bmatrix}i_0\\i_\alpha\\i_\beta\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{pmatrix}\frac{1}{\sqrt{2}}&\frac{1}{\sqrt{2}}&\frac{1}{\sqrt{2}}\\1&-\frac{1}{2}&-\frac{1}{2}\\0&\frac{\sqrt{3}}{2}&-\frac{\sqrt{3}}{2}\end{pmatrix}\begin{bmatrix}i_a\\i_b\\i_c\end{bmatrix} \quad (12)$$

Let the instantaneous real, imaginary and zero sequence power denoted by p, q and p0 respectively. Then the three phase instantaneous power is given by

$$P_{3\phi}=vaia+vbib+vcic \quad (13)$$

Using the transformation

$$P_{3\phi}\,(t)\ =va\ ia+vb\ ib+v0\ i0$$

$$P_{3\phi}\,(t)=p(t)+\ p_0\,(t) \quad (14)$$

The zero sequence components of the voltages and currents do not contribute to the instantaneous powers p and q .The instantaneous imaginary power, q is defined as(15)

$$q=v_\alpha i_\beta-v_\beta i_\alpha=\frac{1}{\sqrt{3}}\{i_a(v_c-v_b)+i_b(v_a-v_c)+i_c(v_b-v_a)\} \quad (15)$$

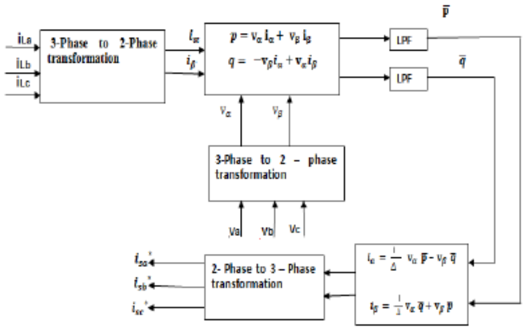

Fig.3 Block diagram of IRPT control algorithm

It represents an energy that may be constant or not and that is being exchanged between the phases of the system. This implies that q does not contribute to the energy transfer between the source and the load at any time. From Eq. (2.20)- (2.21), we write p and q as following

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{pmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{pmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (16)$$

The instan**taneou**s active and reactive powers p and q can be decomposed into an average and an oscillatory component.

P=P- +P~

q=q- +q~

P~ = Mean value of the instantaneous real power. It corresponds to the energy per time unity that is transferred from the power source to the load, in a balanced way, through the a-b-c coordinates (it is, indeed, the only desired power component to be supplied by the power source).

P~ = Alternating value of the instantaneous real power. It is the energy per time unity that is exchanged between the power source and the load, through the a-0-c co- ordinates. Since p" does not involve any energy transference from the power source to load, it must be compensated.

Therefore the reference source currents i sα and i sβ in α-β coordinate are expressed as:

The instantaneous currents on the □ □ □ □ coordinates, *i*□ □ and *i*□ are divided into two kinds of instantaneous current components respectively. Finally, through□ □ □ □ □ □□0 inverse transformation we compute the filter reference currents in

a □ □*b* □ □*c* phase system

$$\begin{bmatrix} i^*_{fa} \\ i^*_{fb} \\ i^*_{fc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} -i_0 \\ i^*_{f\alpha} \\ i^*_{f\beta} \end{bmatrix} \quad (17)$$

Where io is the zero sequence component which is zero in 3- phase 3-wire system. The extracted current components are followed by hysteresis based PWM current controller to generate switching pluses and these signals are applied to STATCOM [5].

The p-q theory has the following limitations

- The source voltages are unbalanced and non-sinusoidal.
- It needs a large number of transducers of measurements and intensive computation.
- It tends to make the system operation complex.

B. Synchronous Rotating Frame Theory

The synchronous reference frame theory is based on the transformation of the currents in synchronously rotating d-q frame. Fig.4. explains the basic building blocks of the theory. If θ is the transformation angle, then the currents transformation from α-β to d-q frame is defined as:

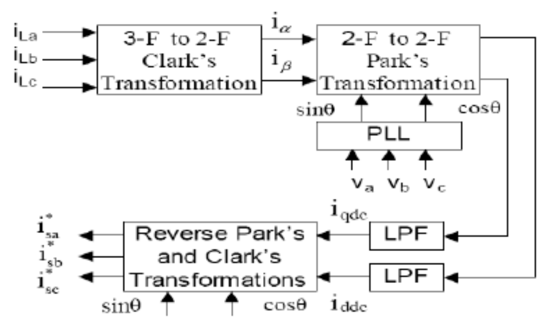

Fig. 4 : Block Diagram of SRF theory

The 3-Phase load currents of system i.e. iLa , iLb, iLc, of stationary reference system in a-b-c coordinates are transformed to two phase system with α-β coordinates, this can be done by algebraic transformation, known as "Clark's transformation" which also produces a stationary reference system again these currents are transformed to synchronously

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rotating reference frame by Park's transformation. The voltage templates (sine and cosine) are generated using phase locked loop (PLL) and then we calculate the id, iq , which are passed through LPF which filter out the harmonics in current signals and again these two phase currents in rotating reference frame are transformed to two phase stationary reference frame using reverse park's transformation and then transformed to three phase coordinates which are called as the reference current signals.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (18)$$

SRF isolator extracts the dc component by low pass filters (LPF) for each id and iq realized by moving averager at 100Hz. The extracted DC componentsiddc and iqdc are transformed back into α-β frame as shown below:

$$\begin{bmatrix} i_{\alpha dc} \\ i_{\beta dc} \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} i_{ddc} \\ i_{qdc} \end{bmatrix} \quad (19)$$

From here the transformation can be made to obtain three phase reference currents in a-b-c coordinates using Reverse Park's transformation and Clark's transformation. The reactive power compensation can also be provided by keeping iq component zero for calculating reference currents. Disadvantages of SRF theory:

- ❖ The generation of voltage templates (sin and cosine terms is crucial)
- ❖ PLL (phase locked loop) is used generation of templates. The operation of PLL is slow and also imposes some of amount of delay in computation
- ❖ Effect of delay due to LPF used for filtering signals in d- q frame
- ❖ Mathematical computations are more and not suitable for 3-phase 4- wire system

C. ADALINE Based Control Algorithm

ADALINE (Adaptive Linear Element) is a single layer neural network. It was developed by Professor Bernard Widrow and his graduate student Ted Hoff at Stanford University in 1960. It is based on the McCulloch–Pitts neuron. It consists of a weight, a bias and a summation function. The basic theory of the proposed decomposer has been based on Least Mean Square (LMS) algorithm and its training through Adaline, which tracks the unit vector templates to maintain minimum error [10]. The block diagram of Adaline based control algorithm is given in Fig 5. The basic concept of theory used here can be understood by considering the analysis in single-phase system which is given as under .The supply voltage may be expressed as:

]Vs=V1Sinwt (10)

Load current is made up of active current (ip), reactive current (iq) for positive sequence and negative sequence current (i−) can be decomposed in parts as: The control algorithm is based on the extraction of current component in phase with the unit voltage template. To estimate fundamental frequency positive sequence real component of load current, the unit voltage template should be in phase with the system voltage and should have unit amplitude further it must be undistorted.

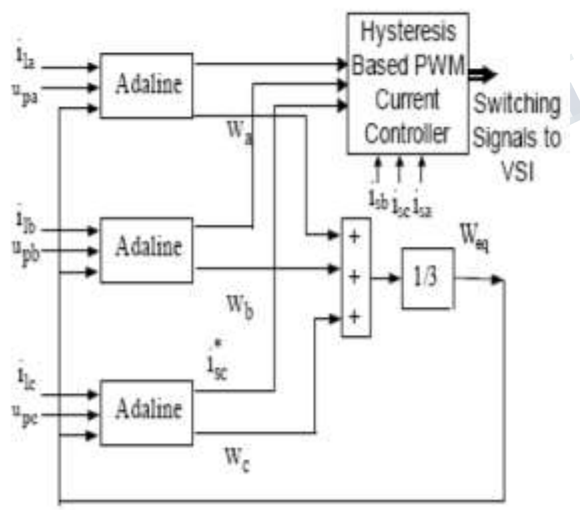

Fig. 5 : Block diagram of the ADALINE theory

For calculation of templates the voltage at Pcc is sensed. The sense voltage is filtered through a band pass filter and the instantaneous rms value is computed. The sensed three phase voltages are divided by this instantaneous rms value to get three phase voltage templates. The initial estimates of active part of current for single phase can be chosen as:

i p = W p u p

Where weight (Wp) is estimated using Adaline. The weight is variable and changes as per the load current and

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magnitude of phase voltage. Algorithm for estimating weights corresponding to fundamental frequency real component of current (for three phase system), based on LMS algorithm tuned Adaline tracks the unit voltage templates to maintain minimum error
iL(K) □ □ wp(K)up(K) (20)

P (k + i) = WP (k) +π{iL(k) -WP (k) up(k) }u P(k) (21)

The value of π(convergence coefficient) decides the rate of convergence and accuracy of estimation. The practical range of convergence coefficient lies in between 0.1 to 1.0 [5]. Three-phase source reference currents corresponding to positive sequence real component of load current may be computed as:

IV. MATLAB BASED MODEL OF STATCOM SYSTEM

Fig. 6 shows the basic simulation model of the STATCOM system. The considered load is a combination of resistance and inductance connected in series for each phase. The load is star connected 32kVA at 0.8pf

The STATCOM model is simulated with above described p-q theory, SRF theory and Adaline based theory. Figs. 7(a)-(c) show the simulation models for these theories. The model assembled using mathematical blocks of SIMULINK block set. The simulation is carried out in continuous mode at maximum step size of 1*10-6 with odel5s (stiff/NDF) solver.

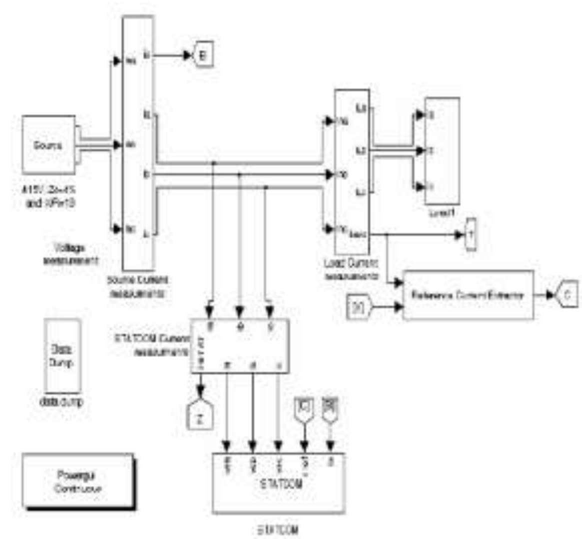

Fig. 6 : MATLAB based model of STATCOM System

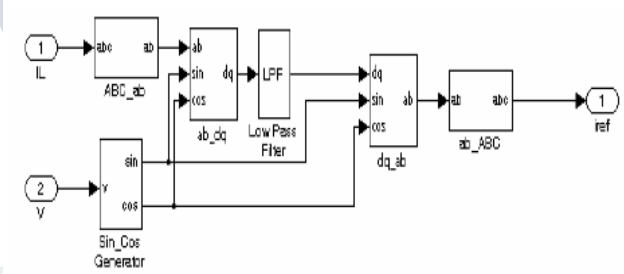

Fig. 7(a) - MATLAB Model of IRP theory

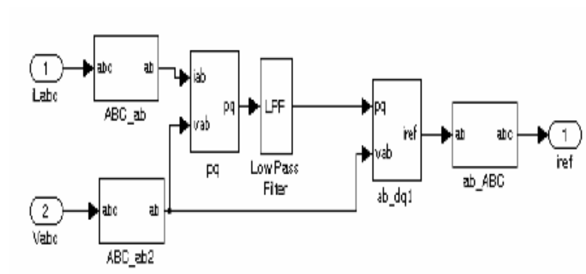

Fig. 7(b) : MATLAB Model of SRF theory

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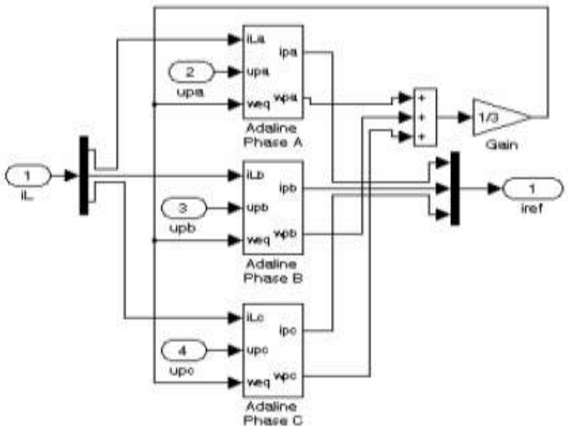

Fig. 7(c) : MATLAB Model of ADALINE theory

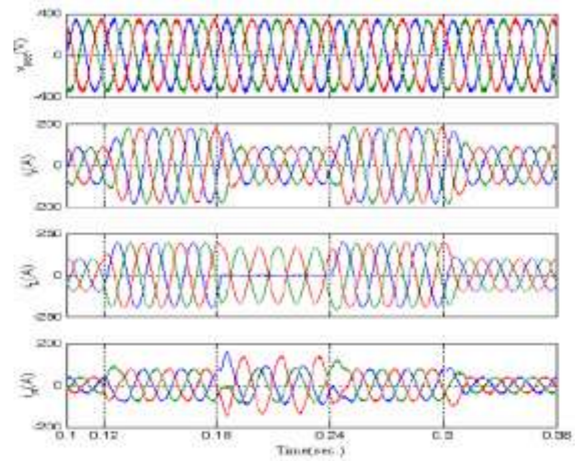

Fig.8 : Reference current extraction using P-Q theory

V RESULTS AND DISCUSSION

The performance of STATCOM is studied for all three methods of control techniques. The following observations are made based on these results.

A. Control of STATCOM by p-q Theory

The operation of STATCOM controlled by the p-q theory is shown in Fig. 8. The unbalance conditions are simulated as per the previous case. The delay in compensation can be seen from source current waveforms. This delay is due to the low pass filter (LPF) used for filtering power signals. Moreover, p-q theory uses voltage signals to compute instantaneous active and reactive powers, any distortion and unbalance in voltage will lead to inaccurate calculation of reference source currents which should contain only real fundamental frequency component of load current [5].

B. Control of STATCOM by SRF Theory

Fig.9 shows the extraction of real fundamental current component of load current by SRF theory. The simulation is carried out for similar load changes and unbalanced conditions as of previous case. The effect of delay due to LPF used for filtering signals in d-q frame can be seen in extracted reference currents waveform in Fig.9. The generation of voltage templates (sine and cosine) plays an important role in calculation of reference source currents. These templates are generated using PLL and therefore the tuning of PLL is crucial [5].

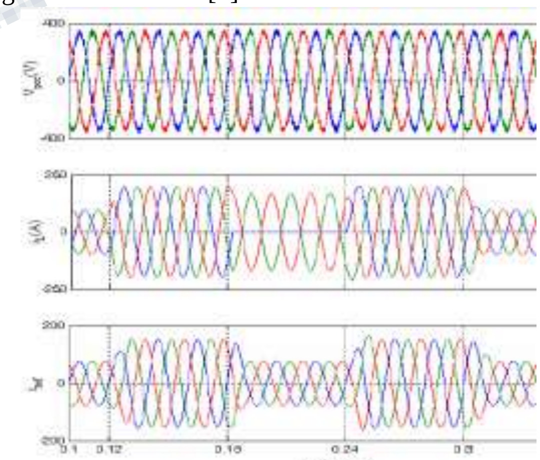

Fig. 9 : Reference current extraction using SRF theory

C. Control of STATCOM by Adaline based Algorithm

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Extraction of reference currents by Adaline based current STATCOM is shown in Fig. 10.

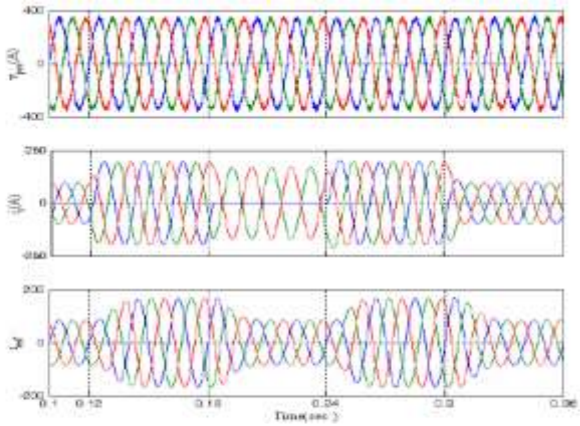

Fig. 10 : Reference current extraction using ADALINE theory

It can be observed that the STATCOM controlled by the Adaline is able to meet the load changes within one cycle of the sine wave. The advantage of the Adaline based extractor is that it requires less computation efforts and therefore the implementation of this technique is much simpler. Moreover, the inherent linearity of Adaline makes it as a fast technique. The speed of convergence can be varied by varying the value of η (convergence-coefficient) [5].

VI CONCLUSIONS

The mathematical derivation of the p-q and SRF theory has been employed to demonstrate the behavior of STATCOM. An Adaline based control technique has resulted in considerable improved performance of STATCOM. The proposed identification method uses the advantage of the ADALINE-Identifier such as simplicity of its structure and consequently less computation time. Moreover, the weights the ADAINE-Identifier have a one-to-one relationship to the parameters of the ARAMA model.

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