Fast Load Voltage Regulation Using STATCOMs

Amit Kumar Jain, *Student Member, IEEE*, and Ned Mohan, *Fellow, IEEE*

***Abstract*-- This paper deals with fast load voltage regulation using a STATCOM. A simplified system representation in a *dq* frame synchronized with the load voltage is used to explain the basis of instantaneous shunt reactive compensation for effecting voltage regulation. Considerations for controller design in terms of bandwidth issues are outlined. Finally, a preliminary controller is designed and simulation results showing its efficacy are presented.**

***Index Terms*—STATCOM control, reactive compensation, flicker control, load voltage regulation.**

I. Introduction`

TIME varying loads such as electric arc furnaces [1], and fluctuating output power of wind generation systems [2] lead to the problem of voltage flicker. Voltage flicker may be thought of as an amplitude modulation process with the voltage magnitude varied in a frequency range from 0.5 to 30 Hz [9]. The magnitude of variations is usually less than 10% and is not important for most household appliances. However, its effect on incandescent lamps causing continuous variation in luminosity is disconcerting to the human eye. In particular, the human eye is extremely sensitive to modulations in the frequency range of 5 Hz to 20 Hz [1]. Reactive power compensation has been suggested and is being used for flicker mitigation. Thyristor based Static VAR Compensators (SVCs) are traditionally used for this purpose [1]. However, these are limited in their control bandwidth and therefore not effective for compensating higher frequency modulations. For higher bandwidth shunt connected Static Compensators (STATCOMs), and series active filters, both based on pulse width modulated converters have been proposed [1]-[3], [5], [9]. This paper concentrates on STATCOMs for voltage flicker compensation. For effecting fast control, the STATCOM is usually modeled using the *dq* axis theory for balanced three-phase systems [4]. This allows definition of instantaneous reactive current injected by the STATCOM. This is important since energy storage or real power capability is not available in STATCOM. The other important feature of this approach is that the system quantities appear as DC in steady state. Methods have also been proposed for unbalanced system conditions, albeit with bandwidth limitations, like the single-phase *dq0* transform in [5].

A. K. Jain is with the Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN 55414. (E-mail: akj@ece.umn.edu).

N. Mohan is with the Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN 55414. (E-mail: mohan@ece.umn.edu).

Most of the literature on STATCOM control concentrates on control of output current and dc bus voltage for given a reactive current reference. Regulation of the load voltage is achieved using a PID controller that generates the reactive current reference. To the author's knowledge, a standard procedure for obtaining the PID parameters based on the system parameters is not available. In addition, it is usually assumed that the instantaneous frequency of the load voltage is constant and equal to the line frequency of the infinite bus. This paper treats the above mentioned issues in some detail with reference to a very simple system model.

Section II describes the representation of the system in a *dq* frame synchronized with the load voltage necessary for fast control of the load voltage magnitude. Section III outlines the considerations for controller design with regard to dynamic compensation, and includes a preliminary controller and associated simulation results.

II. System Model

A. System Description

The system model used here is a simplified version of an actual system consisting of a load supplied on a distribution system. One phase of the model is shown in Fig. 1(a). It consists of the source modeled as an infinite bus with purely inductive source impedance, a load modeled by a resistance, and the STATCOM modeled as a controllable current source. Balanced three phase conditions are assumed and the STATCOM current dynamics are neglected. The following equation describes the dynamics associated with the three phases:

$$L_s \frac{di_{s,abc}}{dt} = -R_L \cdot i_{s,abc} - R_L \cdot i_{SC,abc} + v_{s,abc} \tag{1}$$

Here, $i_{s,abc}$, $i_{SC,abc}$, and $v_{s,abc}$ are vectors consisting of the individual phase quantities denoted in Fig. 1(a), R_L is the load resistance, and L_s is the source inductance. Under the assumption that zero sequence components are not present, the system can be transformed to an equivalent two phase system by applying the following three to two phase transformation to all the variables.

$$v_{s,\alpha\beta} = v_{sa} \cdot e^{j0} + v_{sb} \cdot e^{j2\pi/3} + v_{sc} \cdot e^{j4\pi/3} \tag{2}$$

where the complex number $v_{s,\alpha\beta} = v_{s\alpha} + j \cdot v_{s\beta}$.

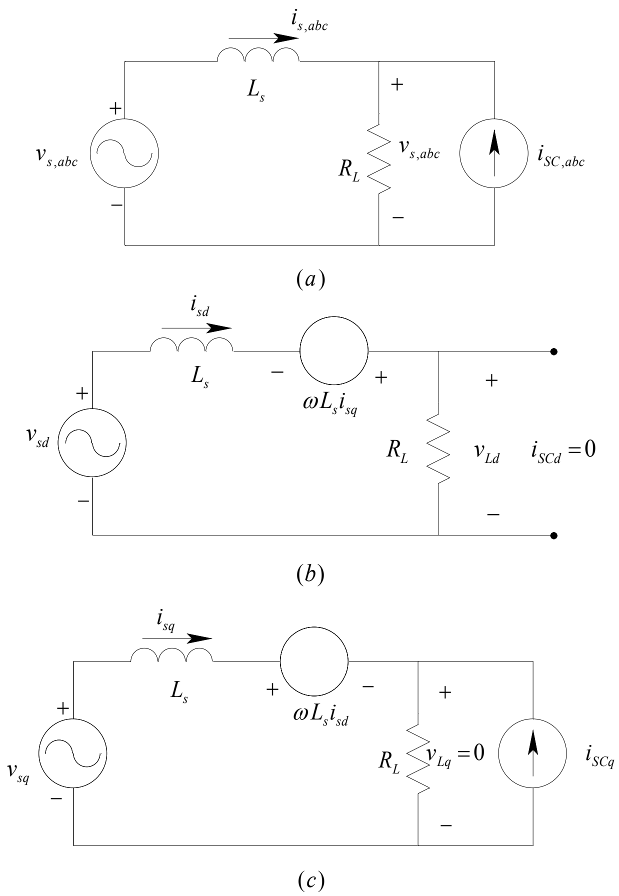


Fig. 1 (a) One phase of the system model; (b) d-axis equivalent circuit; (c) q-axis equivalent circuit.

This is followed by the rotational transformation:

$$v_{s,dq} = v_{sd} + j \cdot v_{sq} = e^{-j\theta} \cdot v_{s,\alpha\beta} \tag{3}$$

where θ is obtained as:

$$\theta = \tan^{-1}\left(v_{s\beta} / v_{s\alpha}\right) \tag{4}$$

Applying the two transformations, (1) can be written as

$$L_s \frac{di_{s,dq}}{dt} = -(R_L + j\omega L_s) \cdot i_{s,dq} - R_L \cdot i_{SC,dq} + v_{s,dq} \tag{5}$$

where ω, a function of time, is given by $\omega = d\theta / dt$ and equals the line frequency in steady state. The equivalent circuits corresponding to the real (*d*-axis) and imaginary (*q*-axis) components of this equation are shown in Fig. 1(b) and 1(c) respectively. If negative sequence components are not present then the variables in (5) are dc quantities in steady state.

B. Remarks About System Representation

Under the condition that the STATCOM supplies only reactive power, so that $i_{SCd} = 0$, the real part of (5) is given by

$$L_s \frac{di_{sd}}{dt} = -R_L i_{sd} + \omega L_s i_{sq} + v_{sd} \tag{6}$$

In addition, definition of θ using (4) ensures $v_{Lq} = 0$ so that v_{Ld} represents the instantaneous magnitude of the phase voltages $v_{L,abc}$. Thus,

$$v_{Ld} = R_L i_{sd} \tag{7}$$

and

$$i_{sq} = -i_{SCq} \tag{8}$$

Eqn. (8) is a consequence of the assumption that the STATCOM current dynamics can be neglected. Thus, for this system i_{sq} cannot be considered an independent state. In a real system, the STATCOM would be coupled to the grid with a capacitor across the load, and the i_{SCq} dynamics will also involve power system parameters corresponding to the source impedance and v_{sq}, the *q*-axis component of the source voltage. Effect of power system parameters on the STATCOM current loop dynamics was studied to some extent in [6]. It was stated that since the power system parameters can vary over a wide range the current control loop design should be robust to the expected variations. Such effects have not been considered here but will be the subject of further investigation. Utilizing (8), (6) can be written as

$$L_s \frac{di_{sd}}{dt} = -R_L i_{sd} - \omega L_s i_{SCq} + v_{sd} \tag{9}$$

Further, (7) and (9) lead to the load voltage equation

$$\frac{dv_{Ld}}{dt} = -\frac{R_L}{L_s} v_{Ld} - R_L \omega i_{SCq} + \frac{R_L}{L_s} v_{sd} \tag{10}$$

III. Controller Design for Load Voltage Regulation

A. Instantaneous Reactive Compensation for Load Voltage Regulation

The basic idea of reactive compensation for voltage regulation comes from sinusoidal steady state. However, from (10) it is evident that regulation can be effected under dynamic conditions as well. A negative value of i_{SCq} (capacitive compensation) leads to an increase in the load voltage. From (9) it is clear that a negative i_{SCq} causes an increase in real power transfer from the source under dynamic conditions. This is to be expected since the increase in real power consumed by the load cannot be supplied by the STATCOM. An increase in reactive power demand of the load can on the other hand be theoretically compensated.

The particular rotation angle θ chosen for the stationary to rotational frame implies that the regulation of the phase voltage magnitudes under dynamic conditions is the same as regulation of v_{Ld}. In much of the published literature (e.g. [1]) the angle θ (or equivalently $\cos\theta$ and $\sin\theta$) needed for the transformation (3) is derived from the line voltage by means of a Phase Locked Loop (PLL). A PLL would necessarily ignore high frequency transients. In [7] the PLL delay is quoted to be more than half a line cycle. In [7] it is also stated that there exists a coupling between i_{SCq} and v_{Lq} due to the line resistance. However, it is not clear why v_{Lq} should not be zero if (4) is used to define θ. To keep this coupling low enough, the voltage regulation bandwidth was limited in [7]. This prevents power system oscillations. As explained in Section I, a STATCOM can regulate voltage by either by supplying reactive power or by effecting a real power transfer from the source. Thus, real power oscillation in the amount necessary to compensate time varying loads or fluctuating generated power is a must unless some energy storage is available. Energy storage for voltage regulation in the presence of fluctuating real power demand has been addressed to some extent in [1].

B. Design of Voltage Control loop: Methods and Dynamic Response Issues

Usually PID controllers are used for the load voltage loop. The voltage magnitude error is the input and the q-axis STATCOM current reference is the output that goes to the STATCOM current controller. A method for deriving the small signal transfer function of the change in load voltage with change in i_{SCq} needed for this approach is described in [10]. However, the application considered there is voltage sags, a slower phenomena compared to voltage flicker, and an assumption is made that ω is constant and equal to the source frequency. Other than experimental procedures like Zeigler and Nichols [8], to the author's knowledge, there is no standard procedure for choosing PID parameters to ensure sufficient bandwidth for flicker compensation and robustness to system variations. Due to the time varying nature of ω equation (10) is non-linear. If the gains are chosen low enough then the variation in $v_{L,abc}$ would be slow and the assumption that ω is constant and equal to the line frequency ω_s would be valid. Clearly, this is not true if a faster response is desired.

The problem of voltage regulation using the dq axis construct may be compared to a certain extent with Rotor Field Oriented Control (RFOC) in Induction Motors (IMs) [11]. The angle used for stationary to rotational frame transformation used in RFOC depends on the slip speed. The slip speed in turn depends on the torque reference, which is proportional to the q-axis component of the stator current. No assumption about rate of change of ω is necessary, and only the leakage inductance and the available inverter voltage restrict the current controller bandwidth. In case of STATCOM, load voltage magnitude is controlled by i_{SCq}, and changes i_{SCq} also affect the angle θ.

C. Preliminary Controller Design and Simulation Results

If the desired constant voltage magnitude corresponds to $v_{Ld}*$, (10) can be rewritten in terms of the error,

$$e = v_{Ld}* - v_{Ld}$$

$$\frac{de}{dt} = -\frac{dv_{Ld}}{dt} = -\frac{R_L}{L_s} e + R_L \omega i_{SCq} - \frac{R_L}{L_s}\left(v_{sd} - v_{Ld}*\right) \quad (11)$$

Thus the current command $i_{SCq} = \frac{1}{\omega L_s}(v_{sd} - v_{Ld}*)$ ensures exponential decay of the error with time constant L_s / R_L. Additional damping may be added by subtracting terms proportional to e/ω from the current i_{SCq}. This controller implicitly assumes knowledge of the power system parameters v_{sd} and L_s, and that ω can be measured or estimated.

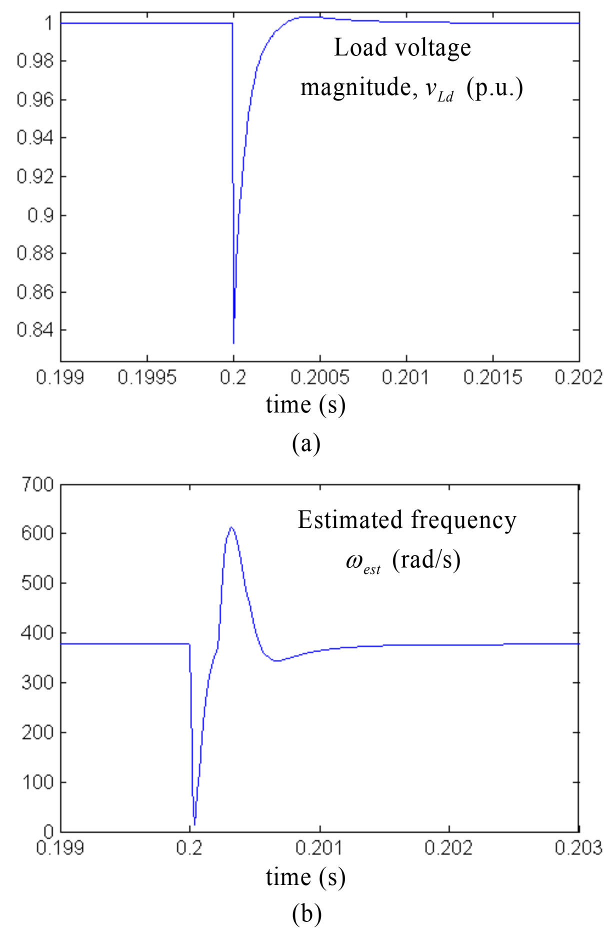
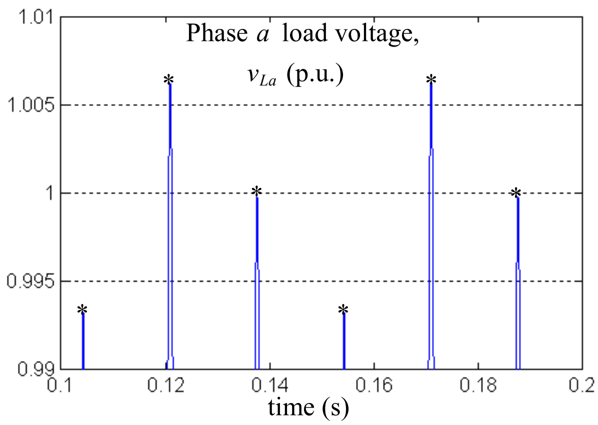


Fig. 2 Step Response: (a) Load voltage; (b) estimated frequency.

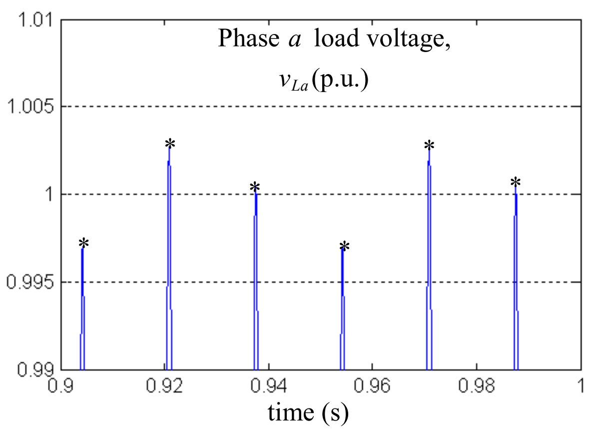
The system was simulated in SIMULINK with the electrical circuit modeled by means of the Power System Blackest. Parameters used were taken from the laboratory prototype used in [6]. The load was made completely resistive. Specifically,

R_L	2.85 Ohm
L_s	0.17 mH
V_s	110 V rms (1 p.u.)

A step change in load, 100% to 120%, was applied by parallel connection of resistors. Step response for the voltage magnitude is shown in Fig. 2(a). Fig. 2(b) shows the estimated instantaneous frequency, ω. As expected, ω deviates considerably from the line frequency ω_s during the transient. Next, a three-phase balanced current source of magnitude equal to the load current and frequency of 20Hz was connected in parallel with the load. This simulates the effect of pulsating load power. Fig. 3(a) and 3(b) show the phase a voltage waveform without and with compensation respectively. The '*' symbols indicate the peaks of the voltage waveform. As seen, oscillations in the voltage magnitude are attenuated substantially. At this point, the controller design is in a preliminary stage and needs further study with respect to disturbance rejection.



(a)



(b)

Fig. 3 Voltage magnitude variation: (a) without compensation; (b) with compensation.

IV. Summary

This paper has given a brief overview of fast load voltage regulation using a STATCOM. Using a simplified system representation, the basis of instantaneous reactive compensation for effecting voltage regulation has been explained. Considerations for controller design have been outlined. A preliminary controller has been designed and corresponding simulation results showing its efficacy have been presented. Work on this problem is still in progress and the following issues are being addressed further:

- Modeling of a system without some of the assumptions made here.
- Comprehensive design of the STATCOM control for output current, the dc bus voltage, and load voltage. Emphasis is on the coupling between the STATCOM and a typical distribution system.
- On-line estimation of power system parameters for controller design.

V. References

[1] G. D. Preville, "Flicker mitigation. Application to a STATCOM," in *Proc. 2001 European Conference on Power Electronics and Applications*, CD-ROM.

[2] C. V. Moreno, H. A. Duarte, and J. U. Garcia, "Propagation of flicker in electric power networks due to wind energy conversions systems," *IEEE Transactions on Energy Conversion*, vol.17, pp.267-72, June 2002.

[3] S. Chen, and G. Joos, "Series and shunt active power conditioners for compensating distribution system faults," in *Proc. 2000 Canadian Conference on Electrical and Computer Engineering*, vol.2, pp.1182-1186.

[4] C. Schauder, and H. Mehta, "Vector analysis and control of advanced static VAR compensators," *IEE Proceedings-C Generation Transmission & Distribution*, vol.140, pp.299-306, July 1993.

[5] C. Hochgraf, and R. H. Lasseter, "STATCOM controls for operation with unbalanced voltages," *IEEE Transactions on Power Delivery*, vol.13, pp.538-44, April 1998.

[6] P. W. Lehn, and M. R. Iravani, "Experimental evaluation of STATCOM closed loop dynamics," *IEEE Transactions on Power Delivery*, vol.13, pp.1378-84, Oct. 1998.

[7] S. Chen, G. Joos, and L. T. Moran, "Dynamic performance of PWM STATCOMs operating under unbalance and fault conditions in distribution systems," in *Proc. 2001 IEEE Power Engineering Society Winter Meeting*, 2001, vol. 2, pp.950-5.

[8] K. Ogata, *Modern Control Engineering*, 3rd ed., New Jersey, Prentice-Hall, 1997.

[9] J. Dolezal, and J. Tlusty, "Background of active power filter control for flicker suppression, in *Proc. 2001 European Conference on Power Electronics and Applications*, CD-ROM.

[10] P.S. Sensharma, K. R. Padiyar, and V. Ramanarayanan "Analysis and performance of distribution STATCOM for compensating Voltage fluctuation," *IEEE Transactions on Power Delivery*, vol. 16, pp. 259-264, April 2001

[11] N. Mohan, *Advanced Electric Drives*, Minneapolis, MNPERE, 2001.