Voltage Regulation With STATCOMs: Modeling, Control and Results	Điều chỉnh điện áp bằng STATCOM: Mô hình hóa, điều khiển và kết quả
Abstract—This paper presents system modeling and control design for fast load voltage regulation using static compensators (STATCOMs). The modeling strategy gives a clear representation of load voltage magnitude and STATCOM reactive current on an instantaneous basis. The	Tóm tắt-Bài báo này trình bày mô hình hóa hệ thống và thiết kế điều khiển để điều chỉnh điện áp tải nhanh sử dụng thiết bị bù tĩnh (các STATCOM). Chiến lược mô hình hóa đưa ra biểu diễn rõ ràng về biên độ điện áp tải và dòng phản kháng STATCOM trên cơ sở tức thời. Phép

particular coordinate transformation employed here also facilitates extraction of linearized system dynamics in conjunction with circuit simulators. It is rigorously shown that the control problem of load voltage regulation using reactive current is nonminimum phase. Linear and nonlinear con-trollers for the regulation problem are designed and compared via simulation results. Internal dynamics of the STATCOM are modeled using the same strategy. Lyapunov based adaptive controllers are designed for controlling the STATCOM reactive current while maintaining its dc bus voltage. Simulation results of the controlled STATCOM integrated with the load bus voltage controller are presented to show efficacy of the modeling and control design.	chuyển đổi tọa độ đặc biệt được dùng ở đây cũng tạo điều kiện thuận lợi để khai thác các tính chất động học của hệ tuyến tính hóa kết hợp với trình mô phỏng mạch. Người ta đã chứng minh một cách chắc chắn rằng vấn đề khó khăn trong điều chỉnh điện áp tải bằng dòng phản kháng là pha không cực tiểu. Các bộ điều khiển tuyến tính và phi tuyến dùng trong việc điều chỉnh điện áp được thiết kế và so sánh thông qua các kết quả mô phỏng. Động học bên trong của STATCOM được mô hình hóa bằng phương pháp tương tự. Trình điều khiển thích ứng dựa trên Lyapunov được thiết kế để điều khiển dòng phản kháng STATCOM trong khi vẫn duy trì điện áp bus một chiều của nó. Chúng tôi trình bày các kết quả mô phỏng của STATCOM điều khiển tích hợp với bộ điều khiển điện áp load bus để biểu diễn hiệu quả của quá trình mô hình hóa và thiết kế điều khiển. load bus: nút tải, nút phụ tải
I. INTRODUCTION POWER distribution system, fast load voltage regulation is required to compensate for time varying loads such as electric arc furnaces, fluctuating output power of wind generation systems, and transients on parallel connected loads (e.g., line start of induction motors) [1]-[3]. Reactive power sources are commonly used for load voltage regulation in the presence of disturbances. Due to their high control bandwidth, static compensators (STATCOMs), based on three phase pulse width modulated voltage source converters, have been proposed for this application [4]-[7]. For effecting fast control, the STATCOM is usually modeled using	[redacted]

the dq axis theory for balanced three phase systems, which allows definition of instantaneous reactive current and instantaneous magnitude of phase voltages (e.g., see [8]).

Most literature on STATCOM control concentrates on control of STATCOM output current and dc bus voltage regulation for a given reactive current reference. This current reference is generated from a PID controller that regulates the load bus voltage.

Aside from experimental procedures like Ziegler and Nichols [9] , to the authors' knowledge, there is no standard procedure for designing a load voltage controller that ensures the required bandwidth and robustness to system variations. For example, in [10], state feedback control is designed utilizing linearized STATCOM dynamics for dc bus voltage regulation and tracking the reactive current to a reference that is generated via a PID controller. The effect of variation in the distribution system parameters is studied only with regard to the internal dynamics of the STATCOM. In [4], the composite system (i.e., the distribution system dynamics and the STATCOM dynamics) was considered for regulation of load bus voltage and STATCOM dc bus voltage. For control design, a small signal model of the distribution system was derived by transforming the equivalent system impedance to a dq frame rotating at the system synchronous frequency in steady state, thereby imposing a limitation on the dynamic response.

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In this paper, a modeling strategy similar to that used for the field oriented control of three phase ac machines is used (i.e., the frequency of the transformation is not assumed to be constant). This gives a clearer representation of instantaneous load bus voltage magnitude and STATCOM reactive current without any restriction on the dynamics. This derived model is exact and can be used for control design using linear or nonlinear techniques. It is shown how circuit simulators with analog behavioral modeling capability can be used to extract linearized sys-temdynamics without the need for writing all state equations explicitly. As a first step, the system model is utilized to address the problem of bus voltage regulation with the STATCOM assumed to be a controlled reactive current source. It is rigorously shown that this control problem is nonminimum phase for certain operating conditions and thus has an inherent limitation on the achievable dynamic response; a physical explanation for this phenomena is also presented. Subsequently, linear and nonlinear controllers are designed and their performance compared via simulation results. The next step involves controlling the STATCOM to behave as a reactive current source while maintaining its dc bus voltage. This problem is addressed by means of a Lyapunov based adaptive controller. The STATCOM control rapidly regulates the reactive current to its reference (computed from the load bus voltage controller) and regulates the dc bus voltage via the real current

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absorbed by the STATCOM. The values of the parasitics used in the controller are obtained on-line via gradient based estimation schemes. The controlled STATCOM is then integrated with the distribution system model and the load bus voltage controller. Simulation results of the integrated system show the efficacy of the strategy.

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

The paper is organized as follows. Section 2 describes the distribution system modeling. The nonminimum phase nature of the system is discussed in Section 3. Section 4 compares the performance of linear and nonlinear controllers for load bus voltage regulation. Nonlinear control of the STATCOM is presented in Section 5. Simulation results of the integrated system are illustrated in Section 6.

II. DISTRIBUTION SYSTEM MODELING

A. System Description

The system considered here is a simplified model of a load supplied on a distribution system. A STATCOM is connected in parallel with the load. One phase of the model is shown in Fig. 1(a). It consists of: the source modeled as an infinite bus with inductive source impedance, the load modeled by a resistance 1, the STATCOM modeled as a controllable current source, and a coupling capacitor. The coupling capacitor is

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included for two reasons: (1) a real STATCOM may have an L-C filter at its output or have fixed compensation capacitors connected in parallel, and (2) if the capacitor is not included, then the line current and the STATCOM output current are not independent [11] and the dq transformation is not well defined. It is assumed that the source, load, and STATCOM are balanced three phase systems. The system dynamics are described by

Here, is,abc,isc,abc,Vs,abc, and vL^abc are vectors consisting of the individual phase quantities denoted in Fig. 1(a), gL = 1/RL is the load conductance, Ls is the source inductance,

1For simplicity of presentation, a purely resisitive load has been considered here; this apparent loss of generality is, however, not restrictive and reactive impedances can be effectively handled as discussed in [12].

Fig. 2. Orientation of reference frames.

Rs is the source resistance, and Cc is the coupling capacitor. Under the assumption that zero sequence components are not present, (1)-(2) can be transformed to an equivalent two phase x-y system by applying the following three to (3)

where the complex number vSjXy = vsx +jvsy. This is followed by a rotational transformation:

(4)

Applying the two transformations, (1) and (2) can be written as

(5)

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where uj = d9/dt is yet to be designed and may be a function of time. The equivalent circuits corresponding to the real (d-axis) and imaginary (g-axis) components of the equation are shown in Fig. 1(b) and (c), respectively

B. Choice of Reference Frame

We choose the dq reference frame similar to that used for field-oriented control of three phase ac machines. Thus, the angle 0 used in (4) is 0 = tan~1(vlv/vlx) implying

VLq=0^ VLq = 0. (7)

Defining a = 0 — ust, where UJS is the frequency of the infinite bus phase voltages, we get v3^q = Vs.e~^a, where Vs is the constant magnitude of the infinite bus voltage. The relative orientation of the vectors VL,dq,vSidq, and the reference frame are shown in Fig. 2. Ignoring losses, a STATCOM only supplies reactive power so that iscd = 0- The system equations can now be rewritten as

(8) (9)

(10)

(11)

(12)

where (12) is derived using (7). It should be noted that UJ varies with time and is different from UJS . Simplified equivalent circuits with this choice of reference frame are shown in Fig. 3.

C. Advantages of the System Representation

Since VLQ = 0, VLd represents the instantaneous magnitude of the phase voltages VL,abc> while iscq denotes the instantaneous reactive current supplied by the STATCOM and is the control input to the system. In the

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absence of negative sequence components, all the state variables in (8)—(11) are constants in

Fig. 3. Simplified equivalent circuits: (a) <i-axis, (b) g-axis.

steady state. Thus, the balanced three phase system is effectively transformed to an equivalent dc system and the control problem is simplified to control of dc quantities as opposed to the sinusoidally varying quantities. (12) defines u, and therefore 0, using quantities in the dq frame so that the dq transformation is a diffeomorphism [13] (i.e., the abc to dq transform and its inverse are continuously differentiable). Thus, (8)—(12) define the system completely and can be used to design linear or nonlinear controllers.

The transformed system can be represented, in the form of equivalent circuits, using circuit simulators with analog behavioral modeling capabilities. The d and q axis equivalent circuits shown in Fig. 1(b) and (c) can be easily derived from the single phase circuit in Fig. 1(a). Inductors and capacitors are augmented by appropriate controlled voltage and current sources connected in series and parallel, respectively. Three phase sinusoidal ac sources with constant amplitude are replaced by controlled dc sources (e.g., vsd = Vs cos a, vsq = — Vs since). Finally, two additional equations corresponding to (11)—(12) are needed to define a and w. Thus, a more complicated system can be modeled without the need for writing all the state equations explicitly.

Since all the states are constant in steady state, operating point

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calculation is possible by equating the state derivatives to zero. This can be done by a "dc bias point calculation” in a circuit simulator. The system can be linearized about calculated operating points to obtain either state space data or bode plots of the linearized system. For this paper, MATLAB/SIMULINK along with the Power System Blockset is used for modeling the equivalent circuits. Fig. 4 shows the SIMULINK block diagram of the system. All results presented in this paper were obtained from the equivalent circuits based model and verified by direct modeling of (8)—(12).

III. NONMINIMUM PHASE NATURE

The distribution system modeled by the dynamics of (8)—(12) has nonminimum phase when V_{Ld} is chosen as the output of the system with i'_{SCq} = —i_{scq} as the control input, i.e., the immediate effect of a step increase in i'_{SCq} is a reduction or "undershoot” in the output after which the output starts increasing and reaches its steady state value. Linearization of the system model revealed that the small signal transfer function ($v_{Ld}(s)$/^$_{SCq}(s)$) has one Right Half Plane (RHP) zero for certain operating conditions. Bode plots of the transfer function for various operating conditions, each corresponding to a different value of I'_{SCq}, are shown in Fig. 5. The system data used are taken from [7] but the load is assumed to be purely resistive. The system parameters are

An inspection of the equivalent

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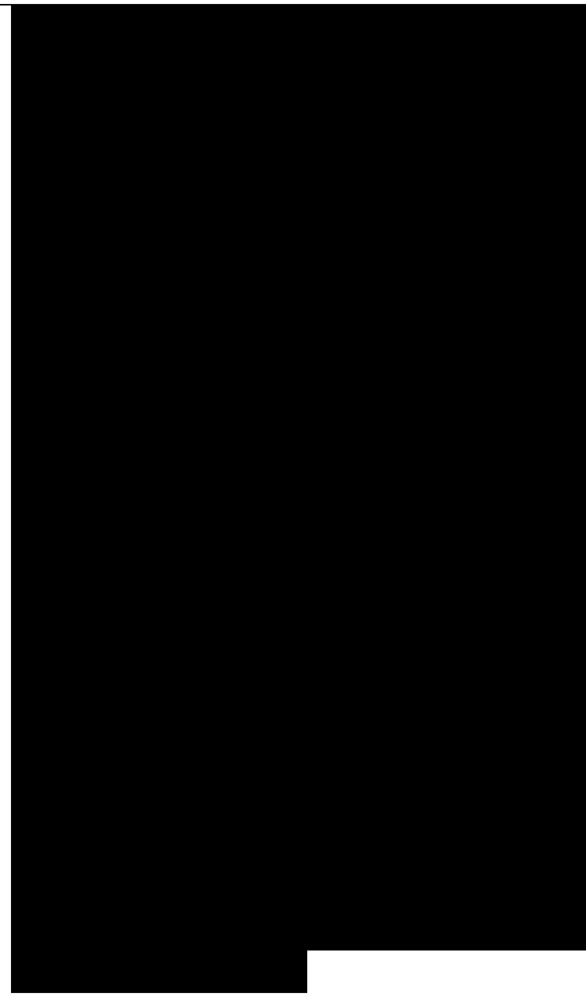
circuits shown in Fig. 3 reveals the peculiar behavior of our system. Assume that at t — 0, i'SCq is increased as a step. Since the line inductance prevents an instantaneous change in isq, the current ooCcVLd reduces instantaneously. Since the coupling capacitor Cc precludes an instantaneous change in VLd> the immediate effect is a reduction in UJ. If the operating condition of the system prior to the step change was such that «sq(0) > 0, then isd starts reducing due to a reduction in value of the controlled voltage source ujLsisq. From the first order dynamics of (8), a decrease in VLd is imminent. Once isq starts increasing due to a reduction of the controlled voltage source ujLsisd, then isd and consequently, v^, start to increase. If the initial system condition is such that isq{0) < 0, then a reduction in UJ does not cause isd to decrease. Thus, the system exhibits nonminimum phase behavior only for isg(0) > 0. Fig. 6(a) and (b) show the simulated step



f'sq

response for the uncontrolled open loop system for cases where >0 and isq{0) < 0 respectively. We refer the interested reader to Appendix A for a nonlinear systems approach to proving the nonminimum phase nature of the system via a study of its zero dynamics.

IV. LOAD VOLTAGE CONTROL

Based on the distribution system model described in the preceding sections, we now proceed to design both linear as well as nonlinear controllers. We then compare the dynamic and steady- state response of the control strategies via simulation results.

A. Linear Controller

Bode Plots of the linearized system shown in Fig. 5 are used along with the Single Input Single Output Design Tool in MATLAB to design a simple linear controller with feedback of the load bus voltage alone. The worst case bode plot, corresponding to the minimum value of RHP zero (1400 rad • s_1), is used. A purely integral compensator with the parameters indicated below suffices

Kj 100

Gain Crossover Frequency 55 [Hz]

Phase Margin (min.) 78°.

B. Nonlinear Controller Design

The nonlinear technique presented here involves a static coordinate transformation followed by feedback linearization [13]

in combination with a gradient based estimator for the load con-ductance. The control input is determined as follows:

Fig. 6. Response of open loop system to step increase in i'SCq: (a) isq (0) > 0,

(b) isq(0) < 0. '

where ism = yj{i2sd + i2aq),p = tan~1(isq/isd), P* = tan_1(i*g/i*d), and kp is a control gain. Variables with the superscript V represent quasi steady state solution obtained by setting the left hand side of (8)—(12) to zero while replacing

Fig. 7. Parallel connection of a time varying load.

gL with its dynamic estimate gL in (8). The load conductance estimate is obtained as

where kg is a positive control gain. Motivation behind this control scheme and detailed stability analysis are

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included in [12].

C. Simulation Results: Controller Comparison

The controllers designed above were verified via SIMULINK based simulations. The nonlinear controller using feedback of the measurable state p (henceforth p-controller), and the output feedback linear controller are compared with respect to regulation of voltage with change in load (#l), change in voltage reference (VLd), and the ability to mitigate voltage flicker due to a parallel connected load with time varying resistance. For study of flicker mitigation, it is assumed that a time varying load is supplied by the same distribution system and connected as shown in Fig. 7. The time varying load has a resistance which is modeled as i^EAC = ^eaco + ^EAC_var sin(27r/fl£), where /a = 8.8 [Hz] represents the frequency at which human eye is most sensitive to the resulting light flicker [1]. System parameters additional to those already stated are listed below

^EACO = RL ^EAC_var = ^EACo/3

LS2 = 18 [mH] /fl = 8.8 [Hz]

For the nonlinear p-controller, the best overall dynamic response was obtained with control gains kp = le5, and kg = 1.8/VS.

Fig. 8 compares the response of the designed controllers to step changes in the reference bus voltage from 1.00 (p.u.) to 0.95 (p.u.) and back to 1.00 (p.u.).

As seen, the p-controller gives the best dynamic response. The linear controller has the same settling time for both step increase and decrease in VLd while the p-controller shows a

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smaller settling time for a step increase in v^d. As the STATCOM cannot supply or absorb real current, isd changes in response to the demanded change in the load current. It should be noted that the case of a step change in v*Ld is only of academic interest. The more important case is that of a step change in load.

Fig. 9 shows the response of the controllers to step changes in load conductance from 100% (nominal) to 150%. Using the linear controller, the load bus voltage error reaches 0.01 (p.u.) in 5 (ms). However, there is a substantial overshoot in VLd and iscq- With the p-controller, the voltage settling time is 5 (ms) and the overshoots observed in VLd, isd, isq, and iscq are significantly lower than those obtained with the linear controller.

Fig. 10 compares the ability of the controllers to mitigate voltage flicker. The commonly used scheme where the STATCOM acts as an active filter (e.g., see [2]) is also compared. In this scheme, the STATCOM supplies the reactive part

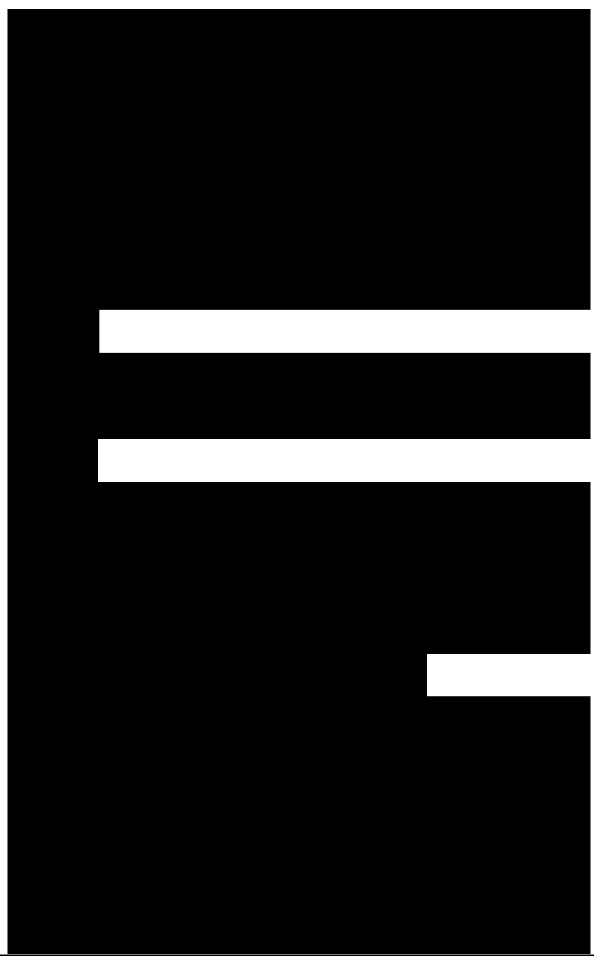

Fig. 8. Step change in vld from 1.00 to 0.95 and back to 1.00 (p.u.).

of the current demanded by the time varying load and does not try to regulate the load voltage explicitly. The percentage variation of voltage magnitude from its reference value is given by AvLd(%) = lOOx (vLd~ vLd)/vld' The percentage mitigation obtained using the three controllers is listed in Table I. From the table, it can be seen that the nonlinear p-controller leads to better mitigation of voltage flicker as compared with the linear controller and the active filter scheme. The 8.8-Hz parallel load appears at beat frequencies in the dq axis frame. Since the open loop gain crossover frequency for the linear controller is 55 (Hz), the STATCOM cannot completely compensate for the disturbance. The controller bandwidth cannot be increased any further due to the nonminimum phase nature of the system. In comparison, the simulation results show that the p-controller is less conservative and gives better performance. Simulations carried out with the system parameters (Vs ,us^Rs,Ls, and Cc) allowed to vary around their nominal values confirmed that the nonlinear controller is robust to changes in system parameters.

V. STATCOM CONTROL

In this section, we address the problem of controlling the STATCOM to act as a reactive current source while maintaining its dc bus voltage. Provided that the STATCOM internal states are measurable, the primary control objective is to rapidly regulate the reactive STATCOM current iscq to the reference value iscq that is generated by the load bus voltage controller. A

TABLE I

FLICKER MITIGATION WITH DIFFERENT CONTROL SCHEMES

Fig. 11. STATCOM circuit representation.

secondary control objective is to bound the dc bus voltage v^c around a desired value denoted by V£c. An additional control objective is to mitigate the dependence of the controller on knowledge of model parameters via the use of adaptive

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control techniques.

A. STATCOM Dynamics

The STATCOM considered here is a three phase inverter with a dc bus capacitor and inductive filter on the line side (Fig. 11). It is assumed that the internal dynamics of the STATCOM are slower when compared to the switching frequency of the inverter [14], so that the STATCOM dynamics can be written as

^dc^dc — PV dc ^abc^SC,abc LscisC,abc = UabcVdc ~ VLd,abc ~ Rsc^SC.abc

Here, v^c is the inverter dc bus voltage, isc is the inverter output current, VLd denotes the load voltage, d denotes the duty ratios for the inverter, while the subscript “abc” implies vectors consisting of individual phase quantities. Parameters in these equations are— C&c dc bus capacitance, p capacitor leakage conductance, Lsc inverter filter inductance, and Rsc combined inverter and inductor parasitic resistance. It should be noted that Rsc and p together model all of the parasitic losses in the STATCOM. After applying the three phase to two phase transformation given by (3) followed by the rotational transformation of (4), the STATCOM dynamics can be rewritten as:

^dc^dc — PV dc 'U'd'i'SCd ^q^SCq (13)

LSc^SCd — VLd Rsc^SCd H” ^Lscig(jq UdV^c (14) LscisCq = — Rsc^SCq ~ uLscisCd + UqVdc (15)

where uo has been previously defined in (11), vac, iscd and iscq represent

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the state variables of the STATCOM, while Ud and uq are the control inputs.

Fig. 12. Block diagram of integrated closed loop controller.

B. Control Design

In order to achieve the primary control objective of regulating the STATCOM reactive current iscq to its reference, one needs to define a regulation error eq as

eq = iscq - i*scq- (16)

From (15), it can be seen that uq can be utilized to achieve the primary control objective. Using (16) and (15) the control input uq is designed as

^q — {^RscisCq ^Lscig(Jd ^q^q) (17)

^dc

where kq is a positive control gain.

The secondary control objective is to bound v^c around its reference. This objective cannot be achieved directly by Ud through (13) as there might be a possibility of iscd going to zero during a transient. By evaluating transfer functions of the system linearized about various operating points, it was observed that the dynamics of (13)—(14) are nonminimum phase when Ud and v^c are chosen as input and output signals, respectively. A stability analysis of the zero dynamics is presented in [15]. Therefore, Vdc is controlled indirectly by controlling iscd• Advantage is taken of the fact that the system states attain constant values in quasi steady state conditions, hence i*scd can be calculated by setting (13)—(15) to zero. Using (14), the control input Ud is then designed as

Ud VAc ^'Ld + RsC%SCd

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U}Lsc'lSCq
digcd ‘ ^

where kd is a positive control gain, p denotes a dynamic estimate for the parasitic conductance which is yet to be designed, and the tracking error = iscd ~ i*scd• T° derive p, we first define an auxiliary signal, v^c to mimic the dc bus voltage

Cdc^dc = —pv dc — Udiscd — UqisCq + kvv&c

where kv is a positive estimation gain, v&c = Vdc ~ Vdc, and the conductance estimation error p = p — p. Based on (19) and the stability analysis carried out in [16], the dynamic estimate for the parasitic conductance is designed as

P — P — kpV dc^dc

with kp a positive constant adaptation gain. Parasitics represented by p and Rsc are expected to vary slowly in steady state; hence, along with an estimator for p, an estimator for Rsc is also designed as:

Rsc — krisCmisCm where kr is a positive constant adaptation gain iscm =

\Ji2SCd + ^SCq^ Cm = \]i*SCd + aiK* ^SCm(t) =

i*scm ~ iscm(t). For a detailed proof of stability of the above control scheme, see [16].

VI. SIMULATIONS OF THE INTEGRATED SYSTEM

The STATCOM model and its control were integrated with the power distribution system and load voltage controller in SIMULINK. The nonlinear bus voltage controller (p-controller) described in Section IV. provide a reactive current reference signal, i^cq> to the STATCOM controller. The other reference input to

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the STATCOM control is the desired constant dc bus voltage, V£c. A block diagram clearly showing the STATCOM and system level control schemes is shown in Fig. 12. Simulation results for this integrated system are presented for two cases, viz., step change in load (g^) and step change in load voltage reference value (VLd). In addition to the system parameters already listed earlier, the following parameters from [4] were used for simulating the integrated system:

Fig. 13. System variables for step change in v*Ld from 1.00 to 0.95 and back to 1.00 (p.u.).

The controller and estimator gains were chosen as

rq = O.le — 3

kv = 0.175 kp = 166.67 kr = 2e3

where and rq are the time constants associated with and eq, respectively.

During each transient, the dc bus voltage v<\c deviates from its reference value V£c. The control inputs uq and Ud as designed in (17) and (18) ensure that both iscd and iscq reach their reference values. It is then easy to see from (13)—(15) that Cdc&v — —pev> where, ev = v^c ~ V£c. This implies that ^dc converges to Vd*c with a purely system dependent time constant rp = Cdc/p , which is of the order of 100 (s) for the system parameters listed above. The slow convergence of ev can also be explained by recalling that (a) v^c is controlled indirectly, and (b) the static relationship of i*scd and leads t0 a di*scd/dvdc value that is of the order of p (« 2e — 5 for our system). Indeed, this poor response was

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manifested in the simulation results. In order to avoid this slow transient, the design of (17) and (18) was modified to use the reference value Vd*c instead of ^dc; this resulted in a satisfactory response for v&c. Details of the stability analysis with this modification are provided in [15].

Fig. 13 shows the response of the system variables to step changes in the reference bus voltage from 1.00 (p.u.) to 0.95 (p.u.) and back to 1.00 (p.u.). As seen, iscq follows its reference value i*SCq very closely, thereby justifying the assumption of

Fig. 14. System variables for step change in gL from 100% to 150%.

the STATCOM being a controlled reactive current source. Thus, using the controlled STATCOM, the bus voltage controller regulates vLd to its reference value VLd. The real current drawn by the STATCOM iscd, follows its reference value with a small lag, as expected from its higher time constant of = 1 (ms). The dc bus voltage v^c is regulated to its reference value of 400 [V]. The values of Rsc and p used in the system model were maintained constant. However, the convergence of the estimates to the actual values after each transient proves the effectiveness of the estimation schemes.

Fig. 14 shows the system response to a step increase in load from 100% to 150%. As seen, the load voltage magnitude VLd is regulated to its reference value. The STATCOM reactive current follows its reference value closely, the real current iscd converges to its reference value i*scd with a small time lag, and the dc bus voltage converges to its reference value.

VII. CONCLUSION

This paper described a method of modeling and control strategies for fast load voltage regulation using STATCOMs. The modeling strategy, similar to that used for field-oriented control of ac machines, clearly defines the bus voltage magnitude and reactive current input from the STATCOM on an instantaneous basis. The particular coordinate transform used also facilitates extraction of linearized system dynamics with the help of circuit simulators having analog behavioral modeling capabilities. Thus, more complex systems can be treated without the need for writing all of the state equations explicitly.

The control problem of load voltage regulation using reactive current as the control input was shown to be the nonminimum phase for certain operating conditions, thereby limiting dynamic response using linear output feedback. Assuming the STATCOM to be an instantaneous reactive current source, a linear controller with output feedback and a nonlinear controller with state feedback were designed and compared via simulations. Results show thatthenonlinearcontrollerhasabettertransientresponseforload changes and leads to better mitigation of flicker arising from time varying loads. Robustness of the nonlinear controller to variation in system parameters was

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confirmed via simulations.
Subsequently, the problem of controlling the STATCOM to make it behave as a controlled reactive current source was addressed. The modeling strategy used earlier was extended to the STATCOM. The STATCOM has two outputs that need to be controlled—the reactive current and the dc bus voltage—and two inputs consisting of the inverter duty ratios transformed to the dq frame. Fast control of the reactive current is achieved using direct feedback linearization with respect to one control input. The other control input is used to indirectly regulate the dc bus capacitor voltage via regulation of the real current to a quasi steady state value. The quasi steady state value depends on par- asitics which are obtained online using gradient-based estimation schemes. Simulation results of the controlled STATCOM integrated with the distribution system have been presented. It is seen that the STATCOM acts as a controlled reactive current source while compensating for internal losses and maintaining the dc bus voltage to a reference value. Furthermore, using the controlled STATCOM, the bus voltage magnitude controller successfully regulates the load voltage for step changes in load conductance and reference bus voltage.

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The basic STATCOMcontrol schemepresentedin SectionVis also applicable for control of three phase PWM rectifiers where a significant load is connected in parallel with the dc bus capacitor (so that p has a

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significantly high value). A bigger challenge that addresses the problem of power quality in a holistic manner revolves around moving away from the assumption of a three phase balanced system and demonstrating stability for unbalanced systems as may occasionally occur in a real distribution system. For flicker mitigation, another challenge is to provide energy storage along with reactive power support that would reduce oscillation of the current drawn from the line.

APPENDIX A SYSTEM ZERO DYNAMICS STABILITY

According to [13], a system is nonminimum phase if the zero dynamics of the system are not asymptotically stable. Assuming isq ± (), zero dynamics of the system are derived as follows. First the output vLd is set to a constant value of v*Ld in (8) which gives i*d = gLV*Ld. Then these values of v*Ld and i*d are used in (9) to obtain iScq in terms of isq and a. Finally, substituting the obtained value ofiscq in (10) and (11) and using (12) for the definition of tu gives the zero dynamics as

Lgisq — Rs'i'sq sin OL

- 9LV*Ld(v*Ld(l + gLRs) - vs cos a)— (20)

1'sq

a = -ios + (v*Ld(l + gLRs) - Vs coso)—^—. (21)

■L's'l'sq

Choosing vLd as a parameter, the equilibrium points for

(20) and (21) are computed. This allows for the local stability analysis of the system via linearization of (20) and

(21) about these equilibrium points.

[redacted]

[redacted]

[redacted]

We begin by defining X = (K)/(\/(l + Rs9l)2 + {usLsgL)2)- For the case when vld > X corresponding to *sg(0) > 0, a pair of eigenvalues is obtained one of which is positive. Since the linearized system corresponding to (20) and (21) is unstable for v*Ld > the nonlinear system given by (20) and (21) is also unstable [13] (i.e., the system (8)—(12) has unstable zero dynamics). For vld < X corresponding to *sg(0) < 0, a pair of complex conjugate eigenvalues with negative real parts is obtained. Since the linearized system corresponding to (20) and (21) is stable for v*Ld < x, the nonlinear system given by (20) and (21) is locally asymptotically stable. For the special case when v Ld — X,the zero dynamics are given by and are asymptotically stable to the equilibrium point. Thus, it can be concluded that the system described by (8)—(12) is a nonminimum phase for *sg(0) > 0.	[redacted]