Improving Transient Stability of Power Systems by using passivity-based Nonlinear STATCOM Controller

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Power Control and Drives

By

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Department of Electrical Engineering

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Under the Guidance of

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CERTIFICATE

This is to certify that the thesis entitled, **“Improving Transient Stability of Power Systems by using Passivity-bassed Nonlinear STATCOM Controller ”** submitted by Sri **D. Raghu Rama Reddy”** in partial fulfillment of the requirements for the award of MASTER of Technology Degree in **Electrical Engineering** with specialization in **“Power Control and Drives”** at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him/her under my/our supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any degree or diploma.

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Raghu Rama Reddy.D

CONTENTS

ABSTRACT

This report presents a novel nonlinear control scheme for designing Static Synchronous Compensators (STATCOM).A passivity-based approach is proposed for designing robust nonlinear STATCOM controller. The mathematical model of STATCOM will be represented by a Euler-Lagrange (EL) system corresponding to a set of EL parameters. The STATCOM modeled in the a–b–c reference frame are first shown to be EL systems whose EL parameters are explicitly identified. The energy-dissipative properties of this model are fully retained under the d-q axis transformation. By employing the Park's transformation, the differential geometry approach is used to investigate the power system dynamics with considering STATCOM under the synchronous d-q frame. Based on the transformed d-q EL model, passivity-based controllers are then synthesized using the technique of damping injection. Two possible passivity-based feedback designs are discussed, leading to a feasible dynamic current-loop controller. Motivated from the usual power electronics control schemes, the internal dc-bus voltage dynamics are regulated via an outer loop proportional plus integral (PI) controller cascaded to the d-axis current loop. The STATCOM controller based on passivity is obtained with a feedback control law from linear system models. The STATCOM controlled by the proposed passivity-based current control scheme with outer loop PI compensation has the features of enhanced robustness under model uncertainties, decoupled current-loop dynamics, guaranteed zero steady-state error, and asymptotic rejection of constant load disturbance. Digital computer simulation for a large operation point variations have been studied the STATCOM controller design. For analysis of the system performance, the PSCAD/EMTDC programme was applied. Simulation results show that the proposed STATCOM controller can effectively enhance transient stability of the power system even in the presence of large operation point variations.

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INTRODUCTION

Recently, Flexible Alternative Current Transmission System (FACTS) controllers have been proposed to enhance the transient or dynamic stability of power systems. During the last decade, a number of control devices under the term FACTS technology have been proposed and implemented. Among all FACTS devices, static synchronous compensators (STATCOM) plays much more important role in reactive power compensation and voltage support because of its attractive steady state performance and operating characteristics. The fundamental principle of a STATCOM installed in a power system is the generation ac voltage source by a voltage source inverter (VSI) connected to a dc capacitor. The active and reactive power transfer between the power system and the STATCOM is caused by the voltage difference across this reactance.

The basic function of the STATCOM is for the line voltage control, which is implemented by an ac voltage controller in the STATCOM by regulating the reactive power exchange between the STATCOM and power system. A second controller installed in the STATCOM is the dc voltage controller, which regulates the dc voltage across the dc capacitor of the STATCOM. In conventional control schemes, both the voltage regulators are proportional integral (PI) type cascaded controllers. Recently, a linear multivariable controller approach has been used for the STATCOM controller design for better performance. However, since the complete model of STATCOM is highly nonlinear, the linear approach obviously dose not lead to better dynamic decoupling.

The dynamical equations of the STATCOM is of nonlinear nature due to the multiplication of the state variables by the control inputs a purely nonlinear approach without ignoring these nonlinearities would be preferable for achieving non local stability or tracking property. The recently developed passivity-based control methodology provides a viable approach to do this job. Successful implementations of this type of control design have been reported in various industrial applications [1]-[3]. Specifically, for control of induction motors, robot arms, and switching power converters, it has been shown how to beneficially incorporate the structural as well as energy properties of the Euler–Lagrange (EL) systems in the controller synthesis. Enhanced robustness and simplified realization in controller implementation are achieved as compared to the commonly used feedback linearizing law due to the avoidance of exact cancellation of system nonlinearities. These attractive features are resulted from the identification of “workless forces” terms appearing in the EL model. As these workless forces have no effect on the energy balance equation and do not affect the stability properties, there is no need to cancel them in the feed forward part of the control law. The approach in designing a passivity-based controller can be summarized in the following two steps. First, model the plant by EL formulation in which the system's energy-dissipative properties are exploited via identification of the Lagrangian and workless force. Second, based on the EL description, the passivity-based control law is derived as a result to reshape the system's natural energy and add the required damping such that desired control objectives are achieved.

In this paper, as an attempt to apply the passivity-based framework for the PWM three-phase ac/dc boost converter, we first derive the EL dynamic expression of the three-phase PWM rectifier. It is shown that a set of EL parameters can be identified to yield corresponding EL structure and establish the passivity properties of the PWM converter in both a–b–c and d–q reference frames [4]. The results also reveal that the three-phase boost ac/dc converter is an under actuated EL system and a dynamic passivity-based controller is synthesized from injecting required damping. The synthesis of the passivity-based controller is carried out from two aspects. To accomplish dc-bus voltage regulation, a scheme (denoted *voltage control*) that directly regulates output voltage is investigated. The resulting zero dynamics are found to be unstable, indicating that this approach is not feasible. For this reason, we proceed to adopt an indirect scheme (denoted *current control*) which performs dc-bus voltage control through regulating input d-q axis line currents. Interestingly, similar situations also appear in the passivity-based stabilization of dc-to-dc boost converters. This is due to both these two types of converters, as output variables expressed in terms of dc output voltage exhibit no minimum phase feature and the passivity-based controller realizes a partial inversion of the system.

In the current control scheme, the output voltage on the dc side will be regulated to the desired level indirectly once d–axis line current tracking is achieved. As an accurate d-axis current command must be pre calculated using the system parameters and load resistance, this kind of indirect output dc voltage control is very sensitive to model uncertainties. A proportional plus integral (PI) controller is cascaded to the d-axis current loop for robust tracking of constant dc-voltage reference. In view of the overall system configuration, it is found that the proposed dc-bus voltage controller is nothing but the outer loop controller. Although this kind of configuration is common, it provides an effective means for improving the performance of passivity based control systems where the state vector of the internal dynamics contains some desired control variables. This modified control scheme will be termed *passivity-based current control with outer loop PI compensation* in the following paragraphs. For example, for the dc-to-dc converter in [5] the internal dynamics were not controlled so that the states of the internal dynamics evolved with convergent rates determined by the inherent time constants.

As the dc-bus voltage dynamics contain a nonlinear input mapping, we establish the global regulation of the outer loop control system under the perfect tracking of inner current loops by applying the results of Desoer and Lin [6]. The proposed passivity-based schemes are then realized in the laboratory via a personal computer with data acquisition boards. A 1.5-kVA prototype PWM ac/dc converter using insulated gate bipolar transistor (IGBT) power switches is built and experiments are conducted to test the performance of the proposed controllers. For the purpose of comparison, the responses of the passivity based current control scheme, passivity-based current control with outer loop PI compensation scheme, and linear PI control scheme of [7] are provided. This paper is organized as follows. Section II presents the derivation of the EL models of the three-phase PWM boost converter in both a–b–c and d–q reference frames. Section III describes the synthesis of passivity-based voltage and current controllers, directly or indirectly achieving dc-bus voltage regulation, respectively. The outer loop PI control of the internal dc-bus voltage dynamics is discussed in Section IV. Experimental results are documented in Section V. A conclusion is finally given in Section VI.

The use of the passivity-based approach to design nonlinear controllers of power converters has been proposed in [8]. In this paper, a passivity-based approach is proposed for designing robust nonlinear STATCOM controller. Mathematically, the STATCOM can be represented by a Euler-Lagrange (EL) system corresponding to a set of EL parameters. Therefore, a STATCOM controller based on passivity consideration is obtained with a feedback control law from linear system models. Simulation results show that the proposed STATCOM controller can effectively enhance transient stability of the power system even in the presence of large operation point variations.

1.1 BACK GROUND

1.1.1 Need for Dynamic voltage compensation

High Intensity Discharge (HID) lamps used for industrial illumination get extinguished at voltage dips of 20%. Also, critical industrial equipment like Programmable Logic Controllers (PLCs) and Adjustable Speed Drives (ASDs) are adversely affected by voltage dips of about 10%. The starting current of the induction motor being 6 times its rated current it provides the sag mitigation. Voltage sag has been defined as a reduction in the voltage magnitude from its nominal value for a duration ranging from a few milli seconds to one minute.

1.1.2 Solution for Dynamic Voltage compensation

Solution approaches to the voltage disturbance problem, using active devices, can involve either i) a series injection of voltage, or ii) a shunt injection of reactive current. The Static Var Compensator (SVC) and the STATCOM are the available shunt compensation devices.

The speed of devices for power quality improvement (FACTS), which was made possible by the evolution of power electronics components, allows for the solving of problems such as voltage stability, transient improvement, oscillations damping and improvement of the lines performance. The term FACTS describes a wide range of controllers, many of which incorporate large power electronic converters, that can increase the flexibility of power systems making them more controllable. Some of these are already well established while some are still in the research or development stage.

In general, FACTS devices possess the following technological attributes:

- Provide dynamic reactive power support and voltage control.
- Reduce the need for construction of new transmission lines, capacitors, reactors, etc which
  - Mitigate environmental and regulatory concerns.
  - Improve aesthetics by reducing the need for construction of new facilities such as transmission lines.
- Improve system stability.
- Control real and reactive power flow.
- Mitigate potential Sub-Synchronous Resonance problems.

To determine which FACTS device would be the most beneficial

- Thyristor Controlled Series Capacitor (TCSC)
- Thyristor Controlled Phase Angle regulator (TCPAR)
- Static Compensator (STATCOM)
- Unified Power Flow Controller (UPFC)

While TCSC provides dynamic control of the series compensated lines, which could increase transfer capability. A TCPAR, is equivalent to a mechanically phase shifting transformer but unlike a UPFC it does not provide controlled reactive power generation. Since a STATCOM mainly provides dynamic reactive power to the Transmission system but as it does not directly control the flow of real power on a transmission line. A UPFC, by providing a combination of real and reactive power control, appeared to be the most useful FACTS device. It could potentially control power flow on the line, reduce the number of lines that can be overloaded, and potentially provide dynamic reactive power control during contingencies.

1.1.3 STATCOM TECHNOLOGY IN BRIEF

STATCOM systems essentially consist of a DC voltage source behind self commutated inverters using insulated gate bipolar transistor (IGBT), gate turn-off (GTO) thyristors and an interconnecting transformer.

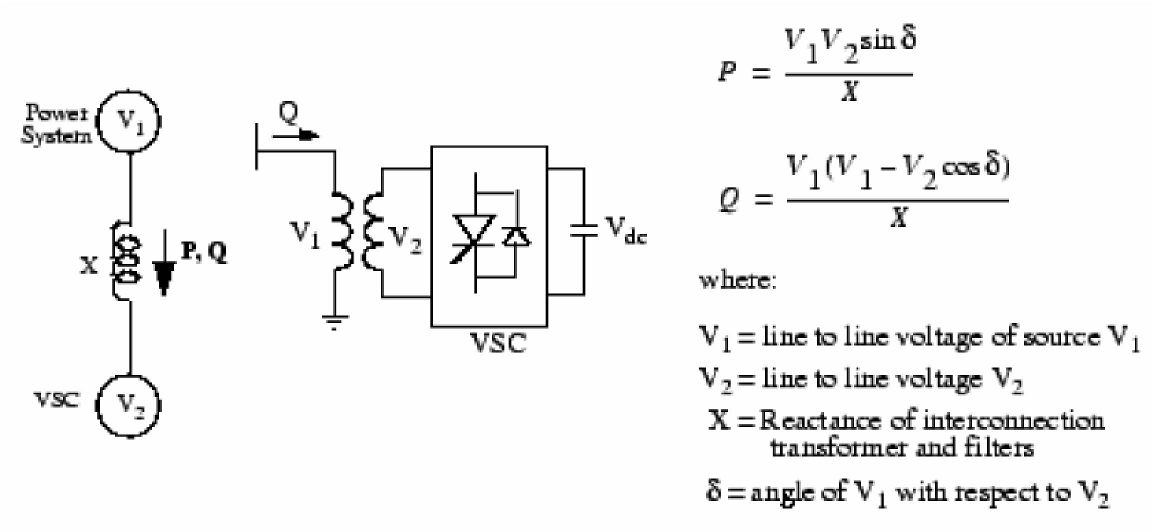


Fig 1.1.3 THE BASIC STATCOM CONFIGURATION

The voltage source inverter set connects to the power system via a multi-winding or two winding inverter transformer, depending upon the application. The figure shows the basic STATCOM configuration. The inverter and DC voltage source can be modeled as a variable voltage source. The power system also can be modeled as a voltage source. An inductor representing the leakage reactance of the transformer connects the two voltage sources.
The principle of operation of the STATCOM is explained on the figure above showing the active and reactive power transfer between a source V1 and a source V2. In this figure, V1 represents the system voltage to be controlled and V2 is the voltage generated by the VSC.

In steady state operation, the voltage V2 generated by the VSC is in phase with V1 (δ=0), so that only reactive power is flowing (P=0). If V2 is lower than V1, Q is flowing from V1 to V2 (STATCOM is absorbing reactive power). On the reverse, if V2 is higher than V1, Q is flowing from V2 to V1 (STATCOM is generating reactive power). The amount of reactive power is given by

$$Q = \frac{V_1(V_1 - V_2)}{X}$$

A capacitor connected on the DC side of the VSC acts as a DC voltage source. In steady state the voltage V2 has to be phase shifted slightly behind V1 in order to compensate for transformer and VSC losses and to keep the capacitor charged. Two VSC technologies can be used for the VSC

1.1.4 STATCOM CONTROL STRATEGIES

- VSC using GTO-based square-wave inverters and special interconnection transformers. Typically four three-level inverters are used to build a 48-step voltage waveform. Special interconnection transformers are used to neutralize harmonics contained in the square waves generated by individual inverters. In this type of VSC, the fundamental component of voltage V2 is proportional to the voltage V_{dc}. Therefore V_{dc} has to be varied for controlling the reactive power.
- VSC using IGBT-based PWM inverters. This type of inverter uses Pulse-Width Modulation (PWM) technique to synthesize a sinusoidal waveform from a DC voltage source with a typical chopping frequency of a few kilohertz. Harmonic voltages are cancelled by connecting filters at the AC side of the VSC. This type of VSC uses a fixed DC voltage Vdc. Voltage V2 is varied by changing the modulation index of the PWM modulator.

GTO-based STATCOM modal is used in transient stability studies. A detailed model of a GTO- based STATCOM is provided in the FACTS demo library.

Because of the sophisticated development in power electronics technology, the static synchronous compensator (STATCOM) is assuming a significant role in reactive power modulation in modern electric power networks. There are several successful applications of STATCOM for reactive power supply load balancing as well as rapid voltage control. The first full-scale STATCOM has become operational since 1991 [10].

The fundamental principle of a STATCOM installed in a power system is the generation of a controllable ac voltage source by a voltage source inverter (VSI) connected to a dc capacitor (energy storage device). The ac voltage source, in general, appears behind a transformer leakage reactance. The active and reactive power transfer between the power system and the STATCOM is caused by the voltage difference across this reactance. The ac voltage control is achieved by firing angle control. Ideally the output voltage of the VSI is in phase with the bus (where the STATCOM is connected) voltage. In steady state, the dc side capacitance is maintained at a fixed voltage and there is no real power exchange, except for losses.

The STATCOM differs from other reactive power generating devices (such as Capacitors, Static Var Compensators etc.) in the sense that the ability for energy storage is not a rigid necessity but is only required for system unbalance or harmonic absorption. As a consequence, the not-a-so-strict requirement for large energy storage device makes STATCOM more robust and it also enhances the response speed.

Basically, there are two control objectives implemented in the STATCOM. One is the ac voltage regulation of the power system at the bus where the STATCOM is connected and the other is dc voltage control across the capacitor inside the STATCOM. It is widely known that shunt reactive power injection can be used to control the bus voltage. In conventional control scheme, there are two voltage regulators designed for these purposes: ac voltage regulator for bus voltage control and dc voltage regulator for capacitor voltage control. In the simplest strategy, both the voltage regulators are proportional integral (PI) type cascaded controllers [11,12] The modeling and control design is usually carried out in the synchronous d - q frame, as it is quite standard. Thus, the shunt current is split into d-axis and q-axis components. The reference values for these currents are obtained by separate PI regulators from dc voltage and ac-bus voltage errors, respectively. Then, subsequently, these reference currents are regulated by another set of PI regulators whose outputs are the d-axis and q-axis control voltages for the STATCOM. Although, this cascade control structure yields good performance, it is not very much effective for all operating conditions because, in general, one chosen set of PI-gains may not be suitable for all operating points. Moreover, it really becomes a hard task to choose the PI gains for the four PI regulators occurring in the cascade structure because of the inherent coupling between the d-axis and q-axis variables. Recently, a linear multivariable controller approach has been used for the control design for better performance. However, since the complete model is highly nonlinear, the linear approach obviously does not lead to better dynamic decoupling. a nonlinear multivariable control technique for STATCOM using feedback linearization approach. The feedback linearization technique is based on the idea of canceling the nonlinearities of the system and imposing a desired linear dynamics to control the system.

The problem of voltage compensation, using a STATCOM, has been addressed in literature. In, a *small-signal* analysis of the system was performed with a *transmission* line, which was modeled as a network. Presence of *right-half plane zeros* in the transfer function was detected and an integral controller, cascaded with a second-order *notch-filter* was proposed. An exclusively experimental study of voltage sag mitigation, using reactive power injection, can be found in. Here, a *distribution* line was considered and modeled as a series reactance. It should be noted that PQ issues are mostly relevant in the distribution system and distribution feeders, of length less than 80 km, can be correctly modeled as a *series impedance*.

The basic function of the STATCOM is for the line voltage control, which is implemented by an ac voltage controller in the STATCOM by regulating the reactive power exchange between the STATCOM and power system. A second controller installed in the STATCOM is the dc voltage controller, which regulates the dc voltage across the dc capacitor of the STATCOM. In conventional control schemes, both the voltage regulators are proportional integral (PI) type cascaded controllers. Recently, a linear multivariable controller approach has been used for the STATCOM controller design for better performance. However, since the complete model of STATCOM is highly nonlinear, the linear approach obviously dose not lead to better dynamic decoupling.

To overcome this limitation, several nonlinear control schemes have been proposed to design the STATCOM controller. The feedback linearization approach, based on the idea of canceling the nonlinearities of the system and imposing a desired linear dynamics to control system, is presented in. The dissipativity-based design, relies on a frequency domain modeling of a system dynamic using positive sequence and negative sequence dynamic components, was applied successfully in.

The use of the passivity-based approach to design nonlinear controllers of power converters has been proposed in. In this paper, a passivity-based approach is proposed for designing robust nonlinear STATCOM controller. Mathematically, the STATCOM can be represented by a Euler-Lagrange (EL) system corresponding to a set of EL parameters. Therefore, a STATCOM controller based on passivity consideration is obtained with a feedback control law from linear system models. Simulation results show that the proposed STATCOM controller can effectively enhance transient stability of the power system even in the presence of large operation point variations.

1.2. OBJECTIVE

In modern electrical distribution power systems there has been a sudden increase of single phase and three-phase linear and non-linear loads. These non-linear loads employ solid state power conversion and draw non-sinusoidal currents from AC mains and cause harmonics and reactive power burden, and excessive neutral currents that result in pollution of power systems. They also result in lower efficiency. Static Synchronous Compensators have been developed to overcome these problems. STATCOM based on voltage controlled PWM converters are seen as viable solution. The techniques that are used to generate desired compensating reactive current or capacitive are based on instantaneous extraction of compensating commands from the distorted currents or voltage signals in time domain. The complete model of STATCOM is highly nonlinear, the linear approach obviously dose not lead to better dynamic decoupling.

In this work a passivity-based approach is proposed for designing robust nonlinear STATCOM controller Therefore, a STATCOM controller based on passivity consideration is obtained with a feedback control law from linear system model can effectively enhance transient stability of the power system even in the presence of large operation point variations.

1.3 THESIS OUTLINE

The body of this thesis consists of the following five chapters including first chapter:

- In chapter 2 the basic theory for passive EL systems is presented. We also present stability theory for passive EL systems.
- In chapter 3 described EL model of the STATCOM in a-d-c reference frame and d-q reference frame.
- In chapter 4 gives the control strategy for STATCOM concerns with the control of ac and dc bus voltage on both sides of STATCOM.
- In chapter 5 simulation results are put and discussed in detail with PI controller to regulates the d-q axis current commands.
- In chapter 6 deals the deals the conclusion and scope for future work.

Chapter 2

INTRODUCTION TO PASSIVITY-BASED CONTROL OF EULER-LAGRANGE SYSTEMS

Why is the theory needed?

EL systems and passive EL systems

Passivity Based Control

The Euler- Lagrange equations

2.1 Why is the theory needed?

In classical control theory, linear models are considered. If the equations describing a system are nonlinear, the system is linearised, which means that the nonlinear equations are approximated with a linear system. This linear system is then used to determine the control laws. The control laws derived from such an approach are sufficient in many practical applications, but in some cases the linear approach is not sufficient. Therefore, a theory for nonlinear control systems is needed. Unfortunately, nonlinear theory for general systems is complicated and rarely useful in engineering applications.

To make nonlinear theory more useful, it is necessary to consider theory for classes of systems with certain properties. The class of passive Euler-Lagrange (EL) systems consists of systems that can be described by the EL equations and do not contain an internal energy source. Examples of passive EL systems are passive electrical circuits, mechanical systems, and robots.

With these special properties in mind, a more useful nonlinear control theory can be presented and nonlinear controllers can be constructed from this theory.

2.2 EL systems and passive EL systems

It is difficult to develop a general nonlinear control theory, because each type of nonlinear system has its own characteristics. Therefore, theories for specialised types of systems are potentially more useful in the analysis of nonlinear systems.

In this report we study a class of systems called Euler-Lagrange systems (EL systems). An EL system is a system whose dynamics are described by the EL equations. These equations are described in this chapter. We also define and investigate a special class of EL systems called passive EL systems. Most of the theory in this report is connected to that class of systems.

2.3 Passivity Based Control

Consider the system

$$\dot{x} = f(x,u)$$

$$y = h(x)$$

Where $f(0,0) = 0$ and $h(0) = 0$. This system is passive if there exists a C^1 positive semi-definite function $V(x)$ (storage function) such that

$$u^T y \geq \dot{V} = \frac{dV}{dx} f(x,u)$$

The system is zero-state observable if no solution of $\dot{x} = f(x,0)$ can stay in the set $\{x \setminus h(x) = 0\}$ other than the trivial solution $x(t) = 0$.

A passive system has a stable origin and we can think of V as the system's energy. We stabilize by using feedback that forces the system to be passive. This approach is stated in the following theorem.

Theorem: If the system

$$\dot{x} = f(x,u)$$
$$y = h(x)$$

is

1) Passive with a radially unbounded positive definite storage function,
2) zero-state detectable

then $x = 0$ can be globally stabilized with $u = -\phi(y)$ where ϕ is any locally Lipschitz function such that $\phi(0) = 0$ and $y^T \phi(y) > 0$ for all $y \neq 0$.

Proof: Use the storage function V as a candidate Lyapunov function for the closed loop system,

$$\dot{x} = f(x, -\phi(y))$$

Then

$$\dot{V} = \frac{dV}{dx} f(x, -\phi(y))$$
$$\leq -y^T \phi(y) \leq 0$$

So that $\dot{V}$ is negative semi-definite. Note that $\dot{V} = 0$ if and only if $y = 0$ and by the assumption that the system is zero-state detectable this implies $x(t) = 0$.

The utility of this theorem is enhanced by transforming a nonpassive system into a passive system. Consider the following state equation in which the control enters in an affine manner,

$$\dot{x} = f(x) + G(x)u$$

and suppose there exists a radially unbounded positive definite C^1 function V(x) such that

$$\frac{dV}{dx} f(x) \le 0$$

For all x.

Create a fictitious output

$$y = h(x) = \left[\frac{dV}{dx} G(x)\right]^T$$

Then we can see that

$$\dot{V} = \frac{dV}{dx} f + \left[\frac{dV}{dx} G(x)\right]^T$$

$$\le y^T u$$

Which implies that the system with input u and output y is passive. We can then apply the above theorem to this system using the fictitious output y in the feedback law.

Example: Consider the system

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = -x_1^3 + u$$

Let

$$V(x) = \frac{x_1^4}{4} + \frac{x_2^2}{2}$$

This implies that

$$\dot{V} = x_1^3 x_2 - x_2 x_1^3 + x_2 u = x_2 u$$

Choose $y = x_2$ and we see that we get a passive system which can be stabilized with the control $u = -kx_2$.

Choosing the output function is useful, but this still limits us to systems that are open loop stable. We can also use feedback to try and transform an unstable system into a passive system. Consider the feedback system.

$$\dot{x} = f(x) + G(x)u$$

If a feedback law

$$u = \alpha(x) + \beta(x)u$$

exists and an output $h(x) = y$ exists such that

$$\dot{x} = f(x) + G(x)\alpha(x) + G(x)\beta(x)u$$
$$y = h(x)$$

is passive and zero-state detectable, then we can use our preceding theorem. This is sometimes referred to as **feedback passivation**. This can often be done for "Hamiltonian" systems that arise in many mechanical applications.

Passivation of $m-$**link Robot:** Consider the following equations of motion for a typical kinematic system,

$$u = M(q)\ddot{q} + C(q,\dot{q})\dot{q} + D\dot{q} + g(q)$$

Consider the tracking problem that seeks to make $e = q - q_r$ small. The tracking error dynamics are

$$M(q)\ddot{e} + C(q,\dot{q})\dot{e} + D\dot{e} + g(q) = u$$

We want to stabilize around $\dot{e} = 0$ and $e = 0$. But this is not necessarily a stable equilibrium point.

Let

$$u = g(q) - K_p e + u$$

Where K_p is a positive definite symmetric matrix and u is an additional control input. Under this change of control variable, we get

$$M(q)\ddot{e} + C(q,\dot{q})\dot{e} + D\dot{e} + K_p e + u$$

We now consider

$$V = \frac{1}{2}\dot{e}^T M(q)e + \frac{1}{2}e^T K_p e$$

as a storage function, then clearly

$$\dot{V} = \dot{e}^T M\ddot{e} + \frac{1}{2}\dot{e}^T M\dot{e} + e^T K_p\dot{e}$$
$$= \frac{1}{2}\dot{e}^T(\dot{M} - 2C)(\dot{e}) - \dot{e}^T D\dot{e} - \dot{e}^T K_p e + \dot{e}^T u + e^T K_p e$$
$$\leq \dot{e}^T u$$

Defining the output as $y = \dot{e}$, we see that the system with input u and output y is passive with V as the storage function. The role of the passifying feedback $g(q) - K_p e$ is to reshape the potential energy to $\frac{1}{2}e^T K_p e$ which has a unique minimum at $e=0$. As a result of this choice of passivating control, the storage function becomes the sum of kinetic energy and reshaped potential energy with $u=0$. $y(t)=0$ if and only if $\dot{e}(t)=0$ which implies that $K_p e(t)=0$ and hence $e(t)=0.$ so this system is also zero-state detectable.

So we've just shown that this mechanical system can be globally stabilizied by the control $u=-\phi(\ddot{e}).$ the choice of $u=-K_d\dot{e}$ results in the actual control law.

$$u = g(q) - K_p(q-q_r) + K_d\dot{q}$$

which is a classical PD controller with a gravity compensation term.

2.4 The Euler- Lagrange equations

The Euler-Lagrange equations were originally used to describe the dynamics of mechanical systems. They can be shown to be equivalent to Newton's second law. The advantage of the EL formulation is that the form of the EL equations is invariant, independently of what coordinates that are used. The EL equations can also be used to describe the dynamics of other physical systems, such as electrical systems. A derivation of the EL equations is beyond the scope of this report.

We recall that a dynamical system with n degrees of freedom can be described by the Euler-Lagrange equations.

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}(q,\dot{q})\right) - \frac{\partial L}{\partial q}(q,\dot{q}) = Q$$

Where q are generalized coordinates, Q are external forces, and $L(q,\dot{q})$ is the Lagrangian function. The Lagrangian is defined as $L(q,\dot{q}) = T(q,\dot{q}) - V(q)$, where
$T(q,\dot{q})$ is the kinetic energy function and $V(q)$ is the potential energy function. Generalized coordinates q are used.

2.4.1 Assumptions and properties

Assumption1 We assume that all kinetic energy functions are of the quadratic form

$$T(q,\dot{q}) = \frac{1}{2}\dot{q}^T D(q)\dot{q}$$

Where $D(q) \in \mathrm{R}^{nXn}$ is called the general inertia matrix. This matrix satisfies
$D(q) = D^T(q) > 0,$ i.e. the matrix is symmetric and positive definite.

Assumption 2 The inertia matrix D(q) is positive definite and symmetric, and is also bounded from above and below, i.e. it satisfies the inequality

$$d_m I < D(q) < d_M I$$

where d_m and d_M are constants.

Assumption 3 The potential energy function V (q) is radially unbounded, globally positive definite, and has a unique minimum at $q = \overline{q}$. It is also assumed that V (q) does not have any other critical points, that is $q = \overline{q}$ is the only solution of $\frac{dV}{dq} = 0$

2.4.2 External forces

There are three different types of external forces that we consider in this report: Control input forces, dissipation forces, and forces from the interaction between the system and its environment (disturbance forces).

The control forces are assumed to enter the system linearly and can thus be described as Mu, where M is a constant control matrix and u is the control vector, that is, a vector containing all the control signals.

The dissipation forces are always of the form $-\frac{dF(\dot{q})}{d\dot{q}}$, where $F(\dot{q})$ is called the Rayleigh dissipation function, which by definition satisfies

$$\dot{q}^T \frac{dF}{d\dot{q}}(\dot{q}) \geq 0$$

Using these three forces, the external forces can be written as

$$Q = \frac{dF}{d\dot{q}}(\dot{q}) + Q_\zeta + M_u$$

Where Q_ζ denotes the disturbance forces.

2.4.3 Dissipativity and passivity

The properties of dissipativity and passivity are very important in the analysis of EL systems. The theory presented in this report is mostly based on passive systems. A passive system is a system that can not store more energy than is supplied to it. In other words, a passive system does not contain an energy source.

Dissipativity : An EL system is dissipative with respect to the supply $s(u,y)$ if and only if there exists a storage function H such that

$$H(x(T)) \leq H(x(0)) + \int_0^T s(u(t), y(t)dt$$

For all u, all $T \geq 0$ and all x_0

Passivity of EL systems: A system is passive if it is dissipative with supply rate $s(u,y) = u^T y$. Because the supplied energy is greater than or equal to the total energy H, the passivity property can also be written as

$$\langle u | G(u) \geq H\left[q(T), \dot{q}(T)\right] - H\left[q(0).\dot{q}(0)\right]$$

2.4.4 Stability properties

Here, we present some stability related properties for unforced EL systems, i.e. $u = 0$. To make it easier to understand, we study stability for fully damped and under damped systems separately.

Fully damped systems are more stable than under damped systems, and the stability properties are simpler. If the system is not fully damped, global asymptotic stability can be ensured if the inertia matrix $D(q)$ has a certain block-diagonal structure. We consider systems with partial damping, i.e. the generalised coordinates q can be partitioned in damped coordinates q_c and undamped coordinates q_p. The indices c and p denote controller and process, respectively. The reason for this notation is that a process can often be considered as an under damped system and the controller a damped one.

The under actuated system imposes some limitations to the modified potential function. The equilibrium of the potential function can only be modified in terms of actuated coordinates which leads to that the closed loop system can only be globally stabilised at a desired equilibrium point chosen in terms of actuated coordinates. These constraints are clearly removed for the fully actuated system where it is possible to modify the potential function in terms of all coordinates. The properties of the potential function and the uniqueness of the equilibrium point.

Chapter 3

EL MODEL OF THE STATCOM

EL Model in a-b-c Reference Frame

EL Model in d-q Reference Frame

3. EL MODELING OF THE STATCOM

3.1. *EL Model in a–b –c Reference Frame*

The power circuit of the three-phase voltage-source PWM ac/dc converter and under consideration is shown in Fig. 1, in which E_m stands for the amplitude of the phase voltage, C is the capacity of the dc-side filter capacitor, and R and L denote the resistance and inductance of the boosting inductor, respectively.

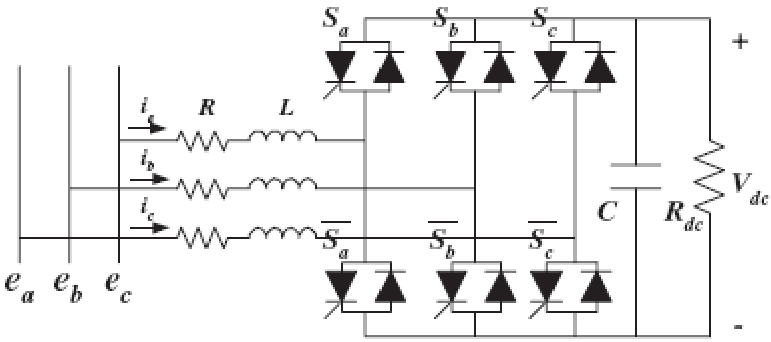


Fig.3.1.1 The STATCOM model circuit.

The input line voltages and currents are expressed by the notations i_k and v_k, $k = a,b,c$ respectively. It is assumed that a resistive load R_L is connected to the output terminals. The bipolar switching functions u_a, u_b and u_c with the definition.

$$u_j = \begin{cases} 1, S_j : closed \\ -1, S_j : open \end{cases} j = a,b,c \qquad (1)$$

represent the switching actions for the six switches. It is assumed that the conducting resistances of the power switches are negligible. The EL description of an electric system is resorted to the Lagrangian $\mathrm{L}(\dot{q}, q)$ of the system, resulting from the difference of the magnetic co-energy of the circuit, denoted by $\mathrm{T}(\dot{q}, q)$ and the electric field energy of the circuit, expressed in terms of $\mathrm{V}(q)$. That is,

$$\mathrm{L}(\dot{q}, q) = \mathrm{T}(\dot{q}, q) - \mathrm{V}(q) \qquad (2)$$

where the vectors q and $\dot{q}$ represent the electric charges and flowing currents, respectively, which constitute the generalized coordinates describing the circuit. In our case, the elements of the vectors q and $\dot{q}$ consist electric charges $q_{La}, q_{Lb}\ q_{Lc}, q_C$ and currents $\dot{q}_{La}, \dot{q}_{Lb}, \dot{q}_{Lc}, \dot{q}_C$ corresponding to the three boosting inductors and filter capacitor, respectively. In view of the circuit configuration of the PWM converter displayed in Fig. 1, the following EL parameters

$$\mathrm{T} = \frac{1}{2}L(\dot{q}_{La}^2 + \dot{q}_{Lb}^2 + \dot{q}_{Lc}^2) \tag{3}$$

$$\mathrm{V} = \frac{1}{2C}{q_C}^2 \tag{4}$$

$$\mathrm{D} = \frac{1}{2}R(\dot{q}_{La}^2 + \dot{q}_{Lb}^2 + \dot{q}_{Lc}^2) + \frac{1}{2}R_L\left\{\dot{q}_C - \frac{1}{2}(u_a\dot{q}_{La} + u_b\dot{q}_{Lb} + u_c\dot{q}_{Lc})\right\}^2 \tag{5}$$

$$\mathrm{F} = \begin{bmatrix} e_a & e_b & e_c & 0 \end{bmatrix}^T \tag{6}$$

Describe the EL dynamics of the PWM converter. The functions D and F are termed Rayleigh dissipation co-function and the generalized forcing function, respectively. The EL model of the PWM converter may then be constructed from the EL equation.

$$\frac{d}{dt}\left(\frac{d\mathrm{L}}{d\dot{q}}\right) - \frac{d\mathrm{L}}{dq} + \frac{d\mathrm{D}}{d\dot{q}} = \mathrm{F} \tag{7}$$

With reference to (1) and (6), the definition $q = [q_{La}\ \ q_{Lb}\ \ q_{Lc}]^T$, and expanding the EL equation (6) with respect to each component in the generalized coordinates q, a set of scalar differential equations

$$\frac{d}{dt}\left(\frac{d\mathrm{T}}{d\dot{q}_{La}}\right) - \frac{d\mathrm{T}}{dq_{La}} + \frac{d\mathrm{V}}{dq_{La}} + \frac{d\mathrm{D}}{d\dot{q}_{La}} = e_a \tag{7.1}$$

$$\frac{d}{dt}\left(\frac{d\mathrm{T}}{d\dot{q}_{Lb}}\right) - \frac{d\mathrm{T}}{dq_{Lb}} + \frac{d\mathrm{V}}{dq_{Lb}} + \frac{d\mathrm{D}}{d\dot{q}_{Lb}} = e_b \tag{7.2}$$

$$\frac{d}{dt}\left(\frac{d\mathrm{T}}{d\dot{q}_{Lc}}\right) - \frac{d\mathrm{T}}{dq_{Lc}} + \frac{d\mathrm{V}}{dq_{Lc}} + \frac{d\mathrm{D}}{d\dot{q}_{Lc}} = e_c \tag{7.3}$$

$$\frac{d}{dt}\left(\frac{d\mathrm{T}}{d\dot{q}_C}\right)-\frac{d\mathrm{T}}{dq_C}+\frac{d\mathrm{V}}{dq_C}+\frac{d\mathrm{D}}{d\dot{q}_C}=0 \tag{7.4}$$

are yielded. A direct calculation of (7)–(7.4) with the EL parameters (3)–(6) gives

$$\frac{d}{dt}\left(L\dot{q}_{La}\right)+R\dot{q}_{La}-R_L\left[\dot{q}_C-\frac{1}{2}(u_a\dot{q}_{La}+u_b\dot{q}_{Lb}+u_c\dot{q}_{Lc})\right]\frac{1}{2}u_a=e_a \tag{7.5}$$

$$\frac{d}{dt}\left(L\dot{q}_{Lb}\right)+R\dot{q}_{Lb}-R_L\left[\dot{q}_C-\frac{1}{2}(u_a\dot{q}_{La}+u_b\dot{q}_{Lb}+u_c\dot{q}_{Lc})\right]\frac{1}{2}u_b=e_b \tag{7.6}$$

$$\frac{d}{dt}\left(L\dot{q}_{Lc}\right)+R\dot{q}_{Lc}-R_L\left[\dot{q}_C-\frac{1}{2}(u_a\dot{q}_{La}+u_b\dot{q}_{Lb}+u_c\dot{q}_{Lc})\right]\frac{1}{2}u_c=e_c \tag{7.7}$$

$$\frac{1}{C}q_C+\left[\dot{q}_C-\frac{1}{2}(u_a\dot{q}_{La}+u_b\dot{q}_{Lb}+u_c\dot{q}_{Lc})\right]=0 \tag{7.8}$$

From the last equation, we get

$$\dot{q}_C-\frac{1}{2}\left(u_a\dot{q}_{La}+u_b\dot{q}_{Lb}+u_c\dot{q}_{Lc}\right)=-\frac{1}{R_LC}q_C \tag{7.9}$$

Substituting the above identity back into (7.5)-(7.7) and noting that $\dot{q}_{Lk}=i_k$ $k=a,b,c,$ and the dc-bus output voltage $v_0=\left(1/C\right)q_c$, the EL model corresponding to the PWM converter under consideration now has the form

$$L\frac{di_a}{dt}+Ri_a+\frac{1}{2}u_av_o=e_a \tag{8}$$

$$L\frac{di_b}{dt}+Ri_b+\frac{1}{2}u_bv_o=e_b \tag{9}$$

$$L\frac{di_c}{dt}+Ri_c+\frac{1}{2}u_cv_o=e_c \tag{10}$$

$$C\frac{dv_o}{dt}-\frac{1}{2}(u_ai_a+u_bi_b+u_ci_c)+\frac{v_o}{R_L}=0 \tag{11}$$

By arranging the parameters in (8)-(11) into the following matrices:

$$\mathrm{M} = \begin{bmatrix} L & 0 & 0 & 0 \\ 0 & L & 0 & 0 \\ 0 & 0 & L & 0 \\ 0 & 0 & 0 & C \end{bmatrix}$$

$$\mathrm{T} = \begin{bmatrix} 0 & 0 & 0 & 0 & \frac{1}{2}u_a \\ 0 & 0 & 0 & 0 & \frac{1}{2}u_b \\ 0 & 0 & 0 & 0 & \frac{1}{2}u_c \\ -\frac{1}{2}u_a & -\frac{1}{2}u_a & -\frac{1}{2}u_a & -\frac{1}{2}u_a & 0 \end{bmatrix}$$

$$\mathrm{R} = \begin{bmatrix} R & 0 & 0 & 0 \\ 0 & R & 0 & 0 \\ 0 & 0 & R & 0 \\ 0 & 0 & 0 & \frac{1}{R_L} \end{bmatrix}$$

One deduces the matrix representation

$$\mathrm{M}\,\dot{w} + \mathrm{J}\ (u)w + \mathrm{R}\,w = \mathrm{F}$$

Where $w = [i_a \ \ i_b \ \ i_c \ \ u_o]^T$

M is a positive-definite diagonal matrix

R is the dissipation matrix

J is the interconnection matrix with switches, and

F is the vector consisting of voltage sources

The skew-symmetry property of the matrix J is a typical feature of an EL system, which has no effect on the following energy balance equation:

$$\mathrm{H}(\mathrm{T}) - \mathrm{H}(0) + \int_0^T x^T \mathrm{R}\, x dt = \int_0^T x^T \mathrm{E} dt$$

Where $\mathrm{H} = \mathrm{T} + \mathrm{V} = \left(\frac{1}{2}\right) x^T \mathrm{D} x$ represents the total energy of the average STATCOM model. The energy balance equation describes that the sum of the stored energy $\mathrm{H}(\mathrm{T}) - \mathrm{H}(0)$ and dissipated energy $\int_0^T x^T \mathrm{E} dt$

Remark 1: Rigorously speaking, the EL (8)–(11) contains discontinuous input terms due to the switching actions u_k, k=a,b,c Analysis of their solutions is quite difficult. A convenient and easy way to handle this problem is the use of averaging analysis. Thus, following the averaging derivation for dc-to-dc switching converters reported in [17], a set of averaged EL equations in the form of (15)–(18) can be obtained with state variables W treated as their averaged values and discrete switch functions u_k, k=a,b,c substituted by their corresponding duty ratio functions. This does not change the structure of the EL model (15)–(18). In order to prevent proliferation in the notation, with some abuse of notation we will directly consider the EL model (15)–(18) as its averaged one. Therefore, in the sequel, the switching functions u_k, k=a,b,c are regarded as duty ratio functions with values in the interval (-1,1) and state vector W represents the averaged state vector.

3.2. EL Model in Rotating d-q Frame

Under a balanced three-phase ac supply, performing the Park's transform

$$\frac{2}{3}\begin{pmatrix} \cos(wt) & \cos(wt - \frac{2}{3}\pi) & \cos(wt + \frac{2}{3}\pi) \\ \sin(wt) & \sin(wt - \frac{2}{3}\pi) & \sin(wt + \frac{2}{3}\pi) \\ 0.5 & 0.5 & 0.5 \end{pmatrix}$$

on (8)–(11), the EL model of the PWM converter in the rotating d–q frame can be expressed as

$$L\dot{x}_1 + Rx_1 + wLx_2 + \frac{1}{2}x_3 u_d = E_m \tag{12}$$

$$L\dot{x}_2 + Rx_2 - wLx_1 + \frac{1}{2}x_3 u_q = 0 \tag{13}$$

$$\frac{2}{3}C\dot{x}_3 - \frac{1}{2}x_1u_d - \frac{1}{2}x_2u_q + \frac{2}{3}\frac{x_3}{R_L} = 0 \qquad (14)$$

In the transformed state equations (12)–(14), the state vector is defined as $x = [x_1\ x_2\ x_3]^T = [i_d\ i_q\ v_o]^T$ and the control input vector $u = [u_d\ u_q]^T$ contains the duty ratio functions $u = [u_a\ u_b\ u_c]^T$ in the synchronously rotating d-q frame. It can be demonstrated that passivity properties of the a-b-c axis EL model are retained under the park's transformation. Representing the d-q model in the following matrix form.

$$\bar{M}\dot{x} + [\bar{J}_1 + \bar{J}_2(u)] + \bar{R}x = E \qquad (15)$$

With

$$\bar{M} = \begin{pmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & \frac{2}{3}C \end{pmatrix} \qquad \bar{J}_2(u) = \begin{pmatrix} 0 & 0 & \frac{1}{2}u_d \\ 0 & L & \frac{1}{2}u_q \\ -\frac{1}{2}u_d & -\frac{1}{2}u_q & 0 \end{pmatrix}$$

$$\bar{J}_1 = \begin{pmatrix} 0 & wL & 0 \\ -wL & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad \bar{R}x = \begin{pmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & \frac{2}{3R_L} \end{pmatrix}$$

and $E = \begin{bmatrix} E_m \\ 0 \\ 0 \end{bmatrix}$

one can easily arrive at the energy balance equation.

$$H(T) - H(0) + \int_0^T x^T R x dt = \int_0^T x^T E dt \qquad (16)$$

Where $H = T + V = \left(\frac{1}{2}\right) x^T D x$ represents the total energy of the average STATCOM model. The energy balance equation describes that the sum of the stored energy $H(T) - H(0)$ and dissipated energy $\int_0^T x^T E dt$

Chapter 4

NONLINEAR STATCOM CONTROLLER DESIGN

4. Controller Design

The control strategy for STATCOM concerns with the control of ac and dc bus voltage on both sides of STATCOM. Our goal is to achieve output voltage tracking via regulation of input line currents. For the error state vector $e = [i_d - i_d^*,\ i_q - i_q^*,\ V_{dc} - V_{dc}^*]^T$, the EL model of the STATCOM model (15) can be written as

$$\begin{aligned} &\mathrm{D}\dot{e} + [\mathrm{J}_1 + \mathrm{J}_2(u)]e + \mathrm{R}e \\ &= \mathrm{E}\left(\mathrm{D}\dot{x}^* + [\mathrm{J}_1 + \mathrm{J}_2(u)]x^* + Rx^*\right) \end{aligned} \tag{17}$$

we see that R injects damping required for asymptotic stability , and that the convergence rate of x^* to zero is improved by increasing R. One may perform a damping injection on (17) by considering the following desired dissipation term

$$\mathrm{R}_d e = (\mathrm{R} + \mathrm{R}_s)e \tag{18}$$

Where $$\mathrm{R}_s = \begin{pmatrix} r_{s1} & 0 & 0 \\ 0 & r_{s2} & 0 \\ 0 & 0 & r_{s3} \end{pmatrix}$$

By substituting (18) into (17), the error dynamics with the injection damping is obtained as

$$\begin{aligned} &\mathrm{D}\dot{e} + [\mathrm{J}_1 + \mathrm{J}_2(u)]e + \mathrm{R}_d e \\ &= \mathrm{E}=\left(\mathrm{D}\dot{x}^* + [\mathrm{J}_1 + \mathrm{J}_2(u)]x^* + \mathrm{R}x^* - \mathrm{R}_s e\right) \end{aligned} \tag{19}$$

In order to obtain desired error dynamics, (19) must require

$$\left(\mathrm{D}\dot{x}^* + [\mathrm{J}_1 + \mathrm{J}_2(u)]x^* + \mathrm{R}x^* - \mathrm{R}_s e\right) = \mathrm{E} \tag{20}$$

Which corresponds to the following scalar differential equations

$$Li_d^* + Ri_d^* + wLi_q^* + \frac{1}{2}V_{dc}^* u_d - r_{s1}(i_d - i_d^*) = E \tag{21}$$

$$Li_q^* + Ri_q^* - wLi_d^* + \frac{1}{2}V_{dc}^* u_q - r_{s2}(i_q - i_q^*) = 0 \tag{22}$$

$$\frac{2C}{3}\dot{V}_{dc}^* - \frac{1}{2}(u_d + u_q) + \frac{2V_{dc}^*}{3R_{dc}} - r_{s3}(V_{dc} - V_{dc}^*) = 0 \tag{23}$$

In the STATCOM control, there are two broad objectives, ac and dc bus voltage that are modified via regulation of input linear currents. Our goal is to achieve regulation of i_d to i_d^* and i_q to i_q^*. From (21) and (22), the control variables u_d and u_q can be solved as

$$u_d = \frac{2}{V_{dc}^*}\left[-Ri_d^* - wLi_q^* + r_{s1}(i_d - i_d^*) + E\right] \tag{24}$$

$$u_q = \frac{2}{V_{dc}^*}\left[wLi_d^* - Ri_q^* + r_{s2}(i_q - i_q^*)\right] \tag{25}$$

By substituting u_d and u_q into (23), the control law is obtained as

$$\begin{aligned} V_{dc}^* = {} & \frac{3i_d^*}{2CV_{dc}^*}\left[-wLi_q^* - Ri_d^* + r_{s1}(i_d - i_d^*) + E\right] \\ & + \frac{3i_q^*}{2CV_{dc}^*}\left[wLi_d^* - Ri_q^* + r_{s2}(i_q - i_q^*)\right] - \frac{V_{dc}^*}{R_{dc}C} \end{aligned} \tag{26}$$

The control block diagram of the proposed control scheme is shown in given Fig

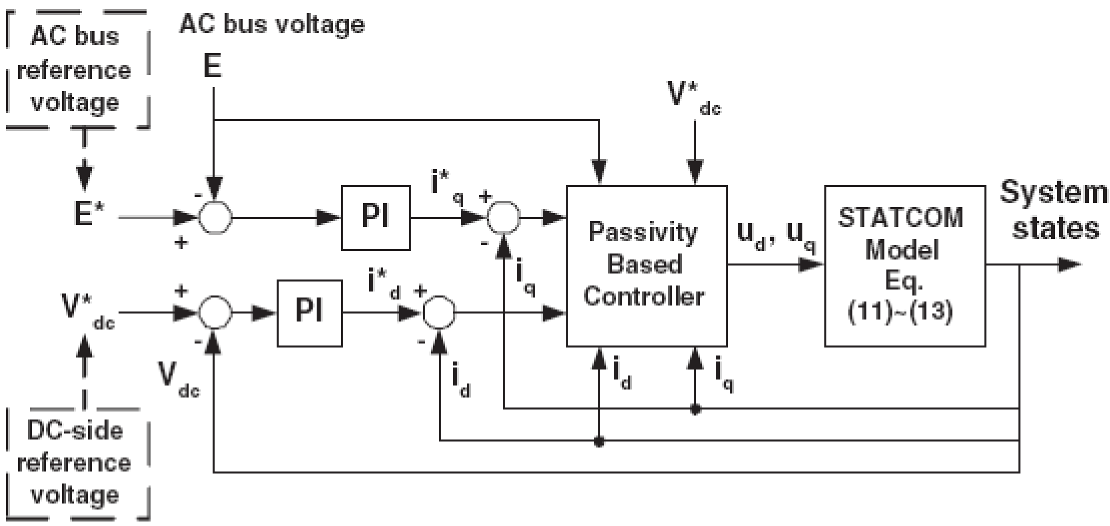


Fig 4.1. Block diagram of the STATCOM controller with PI compensation

Traditionally, the desired current command i_d^* must be predetermined from the steady state solution of STATCOM model (12)-(14). Nevertheless, the parasitic elements in the power system and parameter inaccuracies may led to an incorrect and cause steady-state error in dc-bus output voltage, especially under large disturbance. In order to achieve good tracking performance with strong robustness, the classical PI controller is used to regulate the d-q axis current command i_d^* and i_q^*. Henceforth, the passivity-based control technique mentioned above is readily employed to the design of a STATCOM controller.

Chapter 5

SIMULATION RESULTS AND DISCUSSION

This section will describe the simulation results of the proposed STATCOM controller implemented in PSCAD/EMTDC [16]. Fig. 3 shows the schematic diagram of the studied system used to carry out the transient modeling and analysis of the STATCOM.

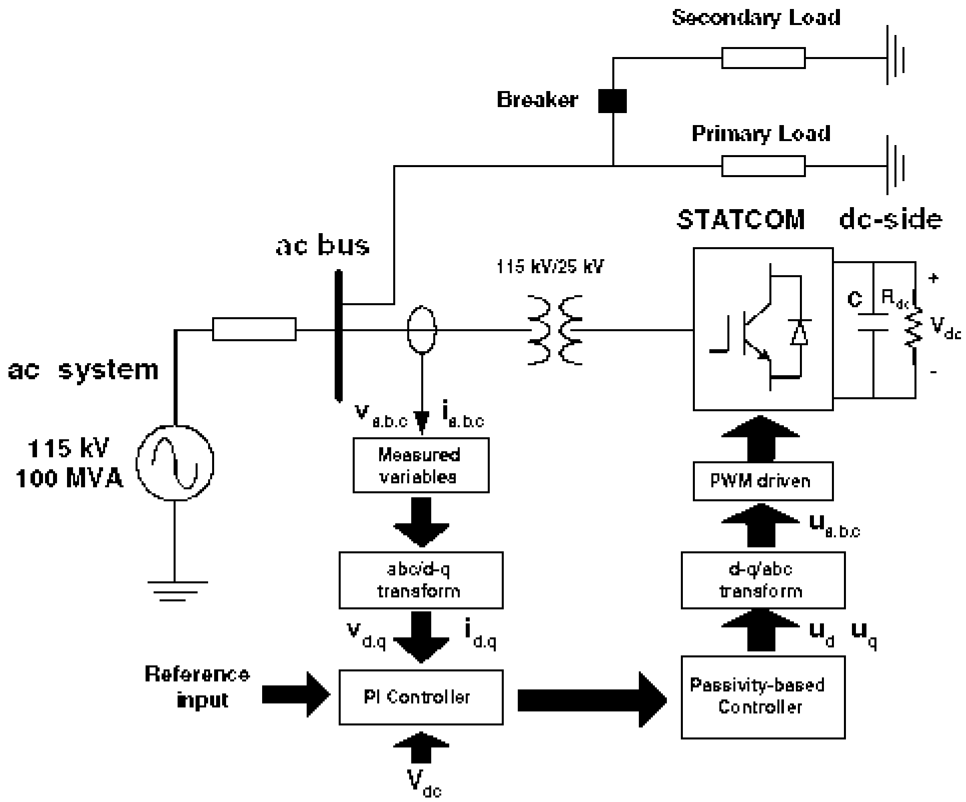


Fig 5.1 . Schematic diagram of the studied system.

The studied system comprises of a 115kV three-phase transmission system, represented as an infinite voltage busbar system connected into the variation load. A two-level VSC-based STATCOM is connected with system provide instantaneous voltage support at the load point. A 300 μF capacitor on the dc side provides the STATCOM energy storage capabilities. In our modeling, the switching losses are taken into account by a shunt dc-side resistance $R_{dc} = 50\Omega$. The breaker controls the connection of the secondary load connected into the system. The aim of the STATCOM is to provide voltage regulation at the load point and alleviate the voltage sag when the load is increased. The system is considered to be operating under balanced conditions and both loads are linear. This STATCOM structure is based on a simple two-level VSI, which is controlled by the proposed control scheme.

The parameters of the studied system are listed in table 5.1

TABLE 5.1

SYSYEM PARAMETERS

Ac source voltage E	115kV
Line resistance R	0.5Ω
Line inductor L	20mH
dc- side capacitor C	300 μF
dc-side resistance R_{dc}	50 Ω
Line frequency w	314 rad/s

A block diagram of the proposed control scheme for designing STATCOM controller is shown in Fig. 3. First, the ac bus voltage, current and the dc-side voltage are measured to construct the STATCOM model based on d-q frame. The control strategy for STATCOM concerns with the control of ac and dc bus voltage on both sides of STATCOM. The dual control objectives are met by generating appropriate current reference and then by regulating those currents in the classical PI controller. The parameters of the PI controller are determined by a repeated study of the system responses under various operating conditions. The PI controller settings, which give the best responses under the various conditions are listed below.

- dc bus regulator: $K_{pd} = 0.01, \quad K_{id} = 0.3$
- ac bus regulator $K_{pq} = 2, \quad K_{iq} = 10$

Now, the switching function u_d and u_q can be determined via the passivity-based controller to counteract various disturbance from (24) and (25). Finally, the sinusoidal pulse width modulation (SPWM) strategy is employed to generate the switching pattern from the switching function $u_a, u_b,$ and u_c.

A diagram of the studied system with a STATCOM in the PSCAD environment is presented in Fig.4.

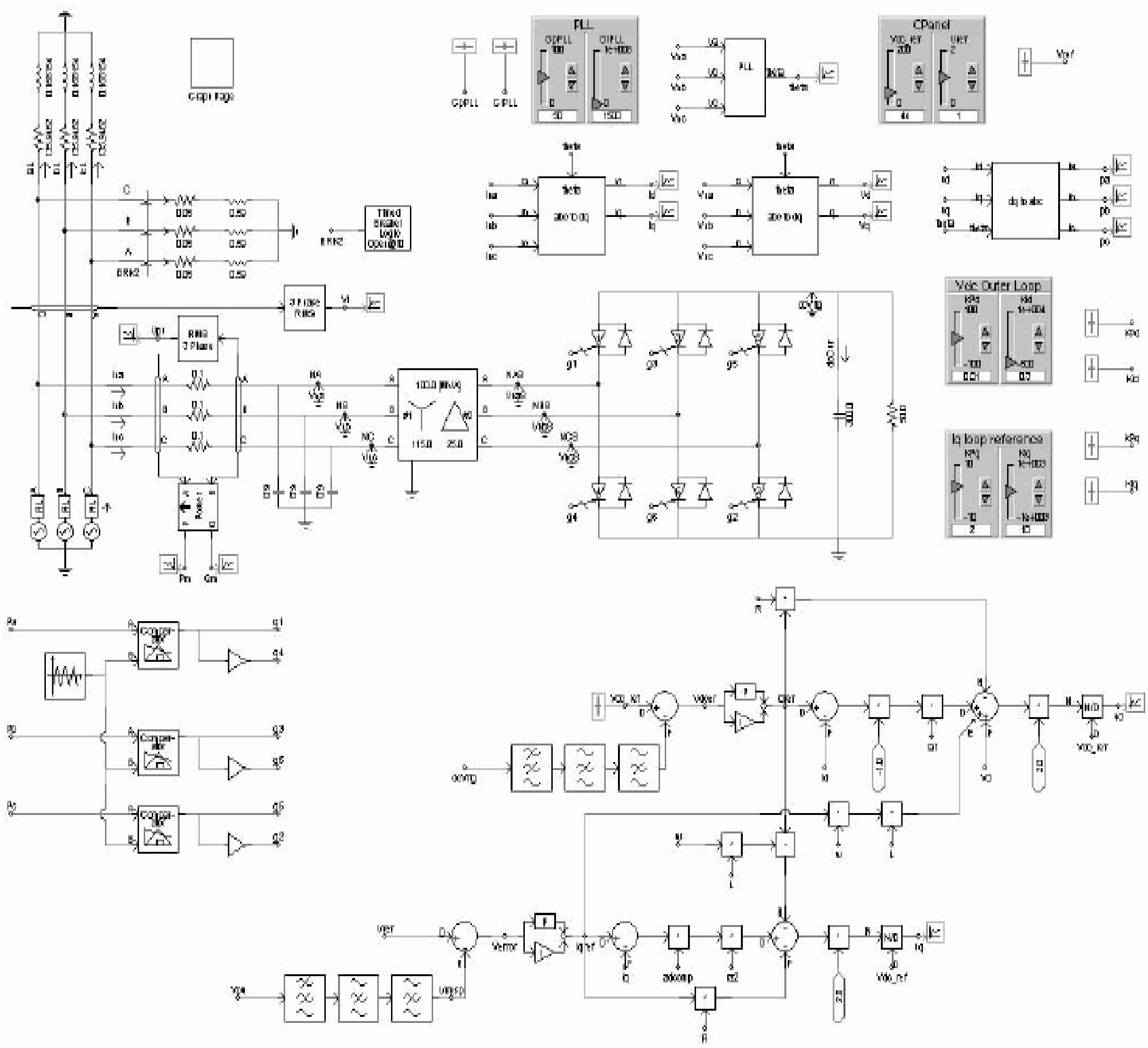


Fig.5.2 Studied system with STATCOM in PSCAD/EMTDC

5.3 SIMULATION RESULTS

Simulation results were carried out to demonstrate that the nonlinear STATCOM controller can provide both voltage regulation and reactive power compensation at the load point when the load is increased. In the simulation interval 0.8-1.2 s, the secondary load is increased by closing the breaker.

The source voltage of the power system is shown in the given fig below.

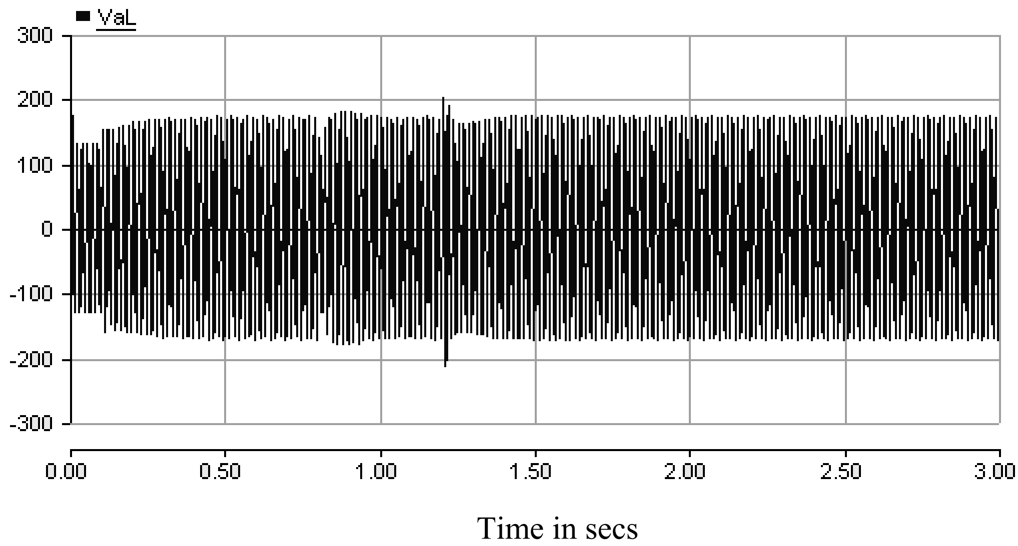


Fig5.3.1. Power system source line voltage in phase a

The secondary load current in phase a when the breaker is closed during the simulation interval 0.8 to 1.2 sec.

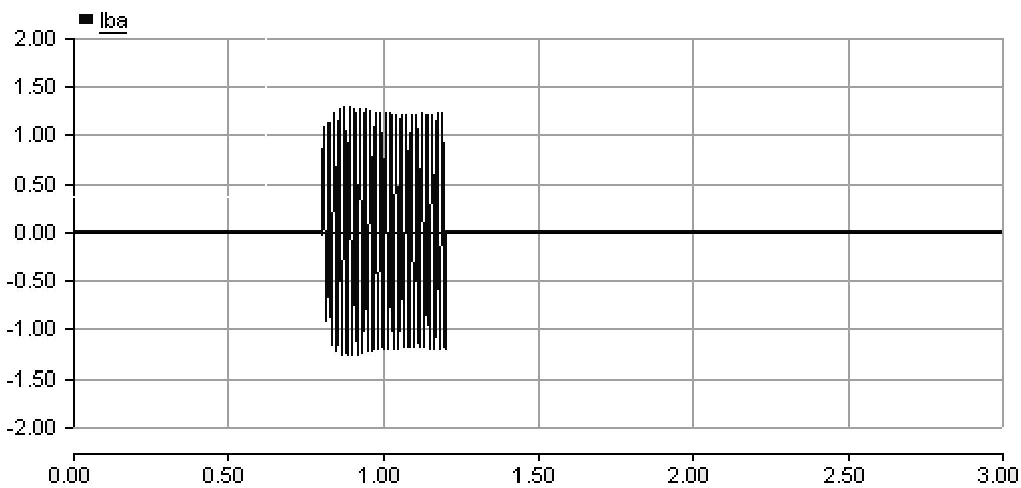


Fig. 5.3.2 Transient response of the secondary load current in phase A

Under this operating condition the voltage at the load point experiences a voltage sag, the d-q axis reference current is injected to regulate the ac bus voltage as shown in Fig. 5.3.3& 5.3.4

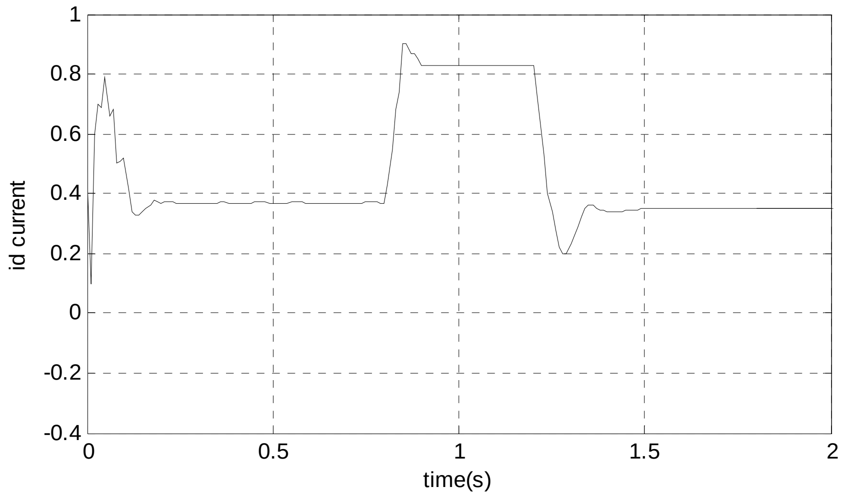


Fig 5.3.3 Transient response for d-axis reference current

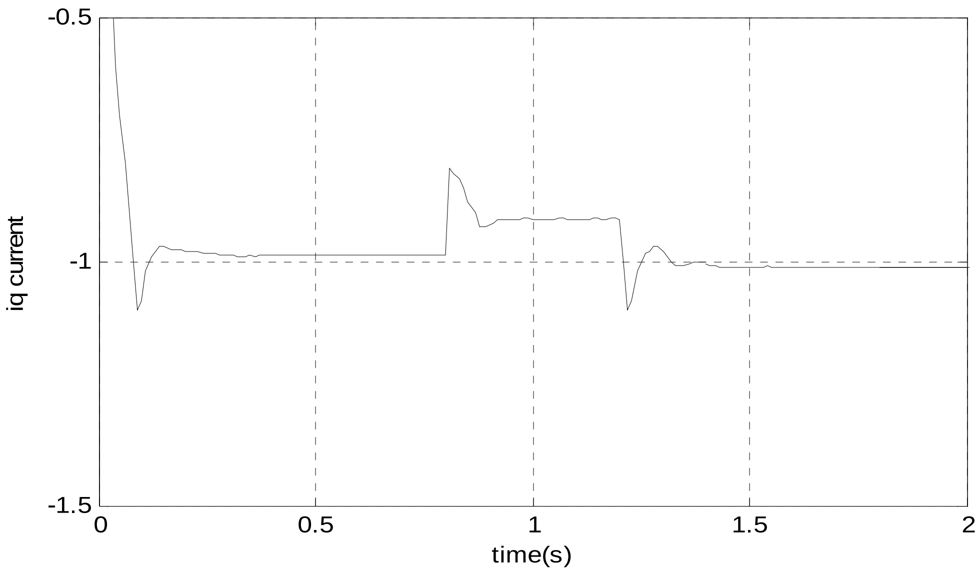
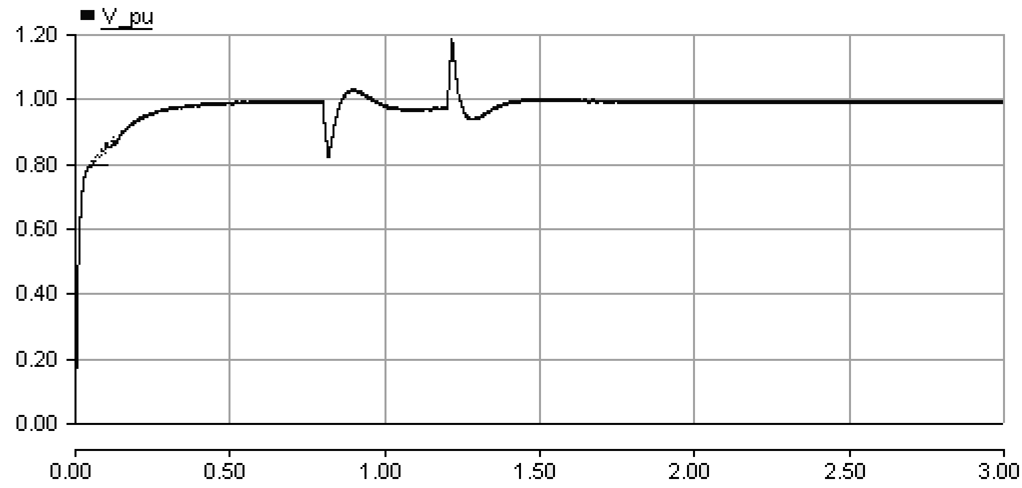


Fig.5.3.4 Transient response for the q-axis reference current.

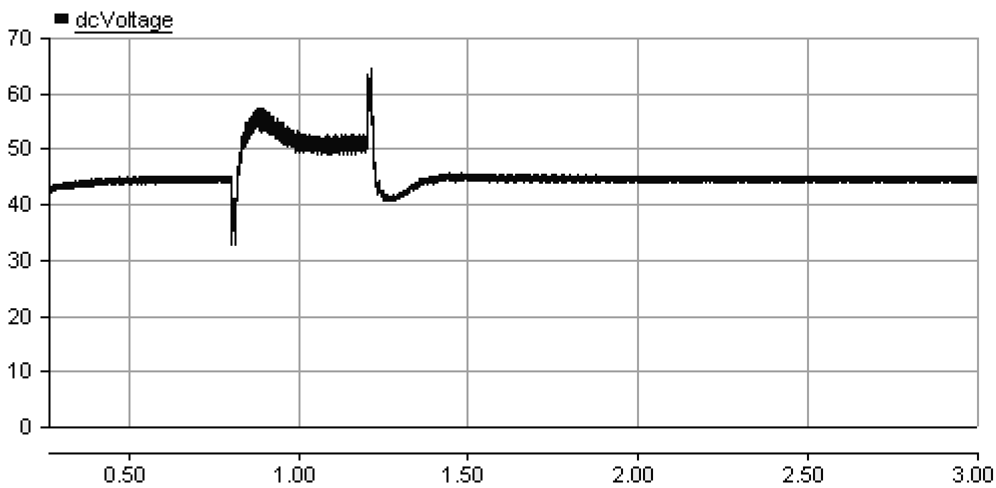
Fast tracking of both d-q axis current commands can be observed. Fig 5.3.5 shows the voltage at the load point with the STATCOM in operation. It can be seen that the voltage sag is being minimized almost completely.



Time in secs

Fig 5.3.5 Transient response for the ac bus voltage.

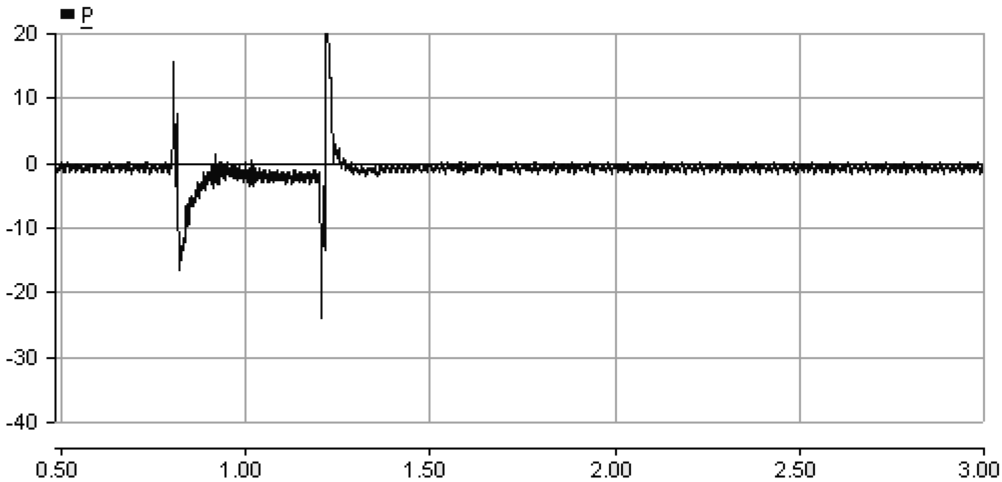
Fig.5.3.6 depicts the voltage of the dc-side capacitor. When STATCOM is full in operation . the dc-side voltage increases to nearly 44KV. The dc-side voltage also has a well damped dynamic behavior, and both undershoot and overshoot are relatively small.



Time in secs

Fig5.3.6. Transient response for the dc-side voltage V_{dc}

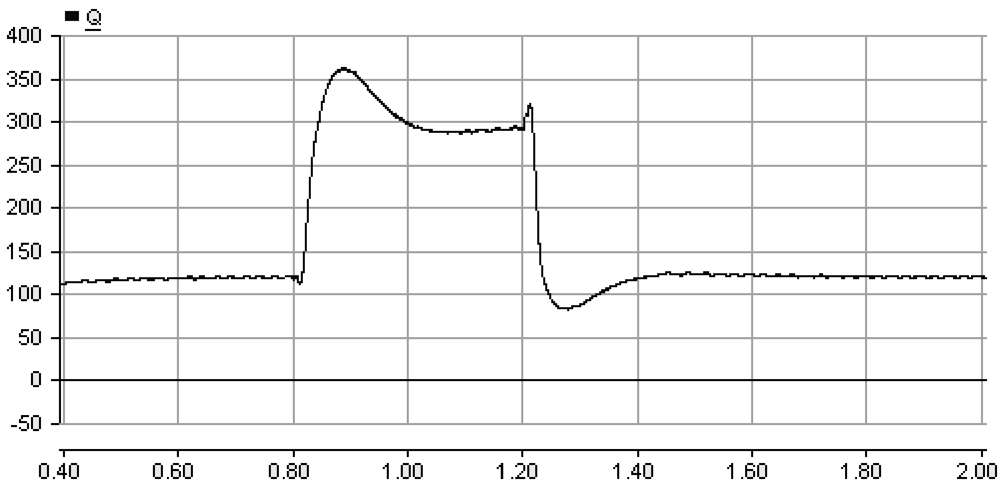
In the simulation inter 0.8-1.2 s, the STATCOM absorbs active power from the ac system to charge the capacitor and maintain the required dc-voltage level.



Time in Secs

Fig5.3.7 Transient response for the active power.

The reactive power exchange rapidly between the ac system and the compensator is shown in Fig.5.1.8



Time in Secs

Fig.5.3.8 Transient response for the reactive power.

It can be observed that the proposed STATCOM controller can rapidly ameliorate disturbance during 0.8-1.2s. Hence, under a large disturbance, the performance of the proposed robust STATCOM controller is still very favorable.

5.2 DISCUSSIONS

First, the ac bus voltage, current and the dc-side voltage are measured to construct the STATCOM model based on d-q frame. The control strategy for STATCOM concerns with the control of ac and dc bus voltage on both sides of STATCOM. The dual control objectives are met by generating appropriate current reference and then by regulating those currents in the classical PI controller.

When the secondary load is increased in the interval 0.8 to 1.2 by closing the breaker, the STATCOM is provide voltage regulation at the load point and alleviate the voltage sag when the load is increased. The system is considered to be operating under balanced conditions and both loads are linear. The reactive power exchange between the ac system and the compensator is discussed. Hence, under a large disturbance, the performance of the proposal robust STATCOM controller is still very favorable.

Chapter 6

CONCLUSION AND SCOPE FOR FUTURE WORK

6.1 CONCLUSION

The ability of the STATCOM device in compensating the power system and stabilize the bus voltage with no transient disturbances on the power system during the transition of increasing or decreasing the reactive power compensation. We have proposed a design procedure of passivity-based nonlinear STATCOM controller for providing both reactive power compensation and voltage regulation at the point of connection. The mathematical model of STATCOM was shown to be EL systems corresponding to a set of EL parameters. The passivity-based control technique allows relatively fast control of the d-q current with good dynamic performance of the overall system. The proposed STATCOM controller, that was investigated by PSCAD/EMTDC has been validated. Simulation result shows that the proposed controller can effectively enhance transient stability of the power system even in the presence of variation load.

6.2 SCOPE FOR FUTURE WORK

Improvement can be brought in the design of the passivity-based nonlinear STATCOM controller. This can also be done either in MATLAB or C. In order to achieve good tracking performance we may also use fuzzy controller to regulate the d-q axis current commands. We also setup the experimental results for the comparison study of the 6-pulse STATCOM.

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