

A Comparison of Two Conventional Power System Control Techniques with Immersion and Invariance

SivaRamaKrishna Paladi, C.Bhavani Manogna

Abstract—The problem of transient stabilization of electrical power systems has been an active area of research in recent years. In this paper we address the performance of different control laws for stabilization of the Single Machine Infinite Bus (SMIB) system and a Two Machine Infinite Bus (TMIB) system with Controllable Series Capacitors (CSCs) as actuators. The SMIB and a TMIB systems are described by the swing equation model and the CSCs are modeled by the injection model. The control laws are derived using two nonlinear control techniques- Immersion and Invariance (I&I) and feedback linearization, and a linear control technique called the power system stabilizer. We compare the three control techniques in terms of their performances.

Index Terms—Power system stabilization, SMIB system, TMIB system, CSC, I&I, Feedback linearization, Power system stabilizer.

1. INTRODUCTION

Traditional analysis and control techniques for power systems are undergoing a major reassessment in recent years. See [1] for an account on the new issues in power system operations. Power systems exhibit various modes of oscillation due to interactions among system components. Many of the oscillations are due to synchronous generator rotors swinging relative to each other. Transient stability is concerned with a power systems ability to reach an acceptable steady-state following a fault. Conventionally, linear controllers are used to improve the transient performance. Given the highly nonlinear nature of the power system models the applicability of linear controller design techniques for transient stability enhancement is severely restricted. On the other hand, the application of more promising nonlinear control methods has attracted much attention in the literature to replace the traditional Automatic Voltage Regulator (AVR) and the Power System Stabilizer (PSS) control structure. In [2], nonlinear control using turbine control, and excitation control has been proposed. In [3]–[6], feedback linearization is applied to the control of a single machine as well as multi-machine systems, using output feedback and state observers.

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How-ever, robustness problems, both against parameter uncertainties and unmodeled dynamics, of these nonlinearity cancellation schemes remains unanswered. In [7], nonlinear controller design of thyristor controlled series compensation is presented for damping inter-area power oscillations.

An important factor, which decides the capacity of a transmission line to transfer the electrical power across the network, the stability margin of the power system, is the reactance of the transmission line. The concept of Flexible AC Transmission System (FACTS) relies on the use of such power electronic devices, and offers greater control of power flow, secure loading and damping of power system oscillations see, e.g., [8]. The devices can be classified into those operating in shunt with the power line such as Static Var Compensator (SVC), in which cases the injected currents are controlled and those operating in series with the power line such as Controllable Series Capacitor (CSC), Unified Power Flow Controller (UPFC), in which cases the inserted voltages are controlled. Recently the application of nonlinear control strategies with controllable series devices has been investigated for improving the transient stability of a power system [7]–[9]. In [10], the IDA-PBC strategy is used for transient stabilization of a synchronous generator using a CSC. Further in [11], the I&I strategy has been used to stabilize the nonlinear swing equation model of the SMIB using a CSC.

In this paper we address the problem of transient stabilization of the SMIB and TMIB systems using CSCs. The power systems are modeled using the swing equation model and the CSCs are modeled by the injection model [12]. We employ a linear control technique called the power system stabilizer [13], and two nonlinear control techniques- feedback linearization [14], and Immersion and Invariance control strategy [15]–[18], to synthesize state feedback control laws for transient stabilization of the single machine infinite bus (SMIB) system and a two machine infinite bus (TMIB) system.

The paper is organized as follows: In Section 2 we briefly introduce the three different control synthesis methodologies. In Section 3 we describe the SMIB system. The control laws are derived using three different control techniques, and comparison study is

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performed at lightly and heavily loaded conditions using simulation plots. In Section 4 we describe the TMIB system. The control laws are derived and comparison study is performed using simulation plots. And finally Section 5 concludes the paper.

II. CONTROL STRATEGIES

In this section we briefly describe the three different control techniques for transient stabilization of power systems. First, we consider linear control technique called the power system stabilizer. Secondly, we consider two nonlinear control techniques- Immersion and Invariance (I&I) and feedback linearization.

A. Power system stabilizer

The power system stabilizer [13] is a widely used linear control technique in which, we use the compensator which is a lead-lag network. We use the state variables of the system as the control signals to power system stabilizer and it has the following form of

$$T(s) = \frac{k_s(1+sT_1)}{(1+sT_2)} \quad (1)$$

where k_s is the gain of power system stabilizer which is to be chosen to provide adequate damping of all critical modes under various operating conditions and the time constants, T_1 and T_2 , are chosen to provide required phase compensation in the range of frequencies that are of interest. Refer to [13],[19] for further details.

B. Feedback linearization:

The basic idea of feedback of feedback linearization technique is to convert the non linear system into linear system by selecting suitable control input which cancels out the nonlinear terms of the system[14]. A non linear single input and single out(SISO) system has the following form:

$$\begin{aligned} \dot{x} &= f(x) + g(x)u \\ y(x) &= h \end{aligned} \quad (2)$$

where $x \in \mathbb{R}^n$ is a state vector, $u \in \mathbb{R}^1$ a control variable, $f(x)$ and $g(x)$ the vector fields on \mathbb{R}^n , y the output and $h(x)$ is scalar function. According to nonlinear control theory, given a differential scalar function $\lambda(x)$ and a vector field $f(x)$, the new scalar function, denoted by $L_f \lambda(x)$, is obtained by the following equation:

$$L_f \lambda(x) = \frac{\partial \lambda(x)}{\partial x} f(x)$$

and called the Lie derivative of function $\lambda(x)$ along the vector field of $f(x)$. Then if a coordinate mapping $z = \phi(x)$ is selected as following :

$$\begin{aligned} Z_1 &= \phi_1(x) = h(x) \\ Z_2 &= \phi_2(x) = L_f h(x) \\ &\vdots \\ Z_r &= \phi_r(x) = L_f^{r-1} h(x) \end{aligned}$$

$$\begin{aligned} Z_{r+1} &= \phi_{r+1}(x) \\ Z_n &= \phi_n(x) \end{aligned} \quad (3)$$

Where $L_f^r h(x)$ denotes r th order lie derivative of $h(x)$ along find $\phi_{r+1}, \dots, \phi_n$ fulfill

$$L_g \phi_i(x) = 0, \quad r < i \leq n$$

Where $L_g \phi_i(x)$ denotes Lie derivative of $\phi_i(x)$ along g and the jacobian matrix at the point $x = x_0$ $J_{\phi} = \frac{\partial \phi(x)}{\partial x}$ not singular, then the original nonlinear system is transformed into a linear system using following control law:

$$u = \frac{-L_f^r h(x) + v}{L_g L_f^{r-1} h(x)} \quad (4)$$

where $v = L_f^r h(x) + L_g L_f^{r-1} h(x)u$. Further details on feedback linearization could be found in [7],[14].

C. Immersion And Invariance:

Immersion and invariance[15] relies upon the notions of system immersion and manifold invariance. The basic idea of I&I is based on (a) immersing a lower order desired target dynamics onto a manifold in the original space, and (b) matching the closed-loop system with the immersed system asymptotically. The control objective is to make the immersed manifold attractive and invariant. The control objective is to make the immersed manifold attractive and invariant. The main result of [1] is now stated .

Theorem:[15] Consider the state space model of the system

$$\dot{x} = f(x) + g(x)u \quad (5)$$

where $f(x)$ and $g(x)$ are smooth functions, with state $x \in \mathbb{R}^n$ and control $u \in \mathbb{R}^m$, with an equilibrium point, $x_* \in \mathbb{R}^n$ to be stabilized. Let $p < n$ and assume we can find mappings

$$\begin{aligned} \alpha: \mathbb{R}^p &\rightarrow \mathbb{R}^p, \quad \pi: \mathbb{R}^p \rightarrow \mathbb{R}^n, \quad c: \mathbb{R}^p \rightarrow \mathbb{R}^m, \\ \phi: \mathbb{R}^n &\rightarrow \mathbb{R}^p, \quad \Psi: \mathbb{R}^n \times \mathbb{R}^{n-p} \rightarrow \mathbb{R}^m \end{aligned}$$

such that the following hold.

1) (H1) (Target system) The system

$$\dot{\xi} = \alpha(\xi) \quad (6)$$

with state $\xi \in \mathbb{R}^p$ has asymptotically stable equilibrium at $\xi_* \in \mathbb{R}^p$ and $x_* = \pi(\xi_*)$.

2) (H2) (Immersion condition) For all $\xi \in \mathbb{R}^p$

$$f(\pi(\xi)) + g(\pi(\xi))c(\pi(\xi)) = \frac{\partial \pi}{\partial \xi} \alpha(\xi). \quad (7)$$

3) (H3) (Implicit Manifold) The following set identity $\{X \in \mathbb{R}^n \mid \phi(x) = 0\}$

$$= \{X \in \mathbb{R}^n \mid x = \pi(\xi) \text{ for some } \xi \in \mathbb{R}^p\} \quad (8)$$

4) (H4) (Manifold attractive and trajectory boundedness all

Trajectories of the system

$$\dot{z} = \frac{\partial \phi}{\partial x} [f(x) + g(x)\Psi(x, z)] \quad (9)$$

$$\dot{x} = f(x) + g(x)\Psi(x, z) \quad (10)$$

are bounded and satisfy

$$\lim_{t \rightarrow \infty} z(t) = 0 \quad (11)$$

Where $z = \phi(x)$ and $u = \psi(x)$.

Then x_* is an asymptotically stable equilibrium of the closed loop system

$$\dot{x} = f(x) + g\psi(x, \phi(x)).$$

The result in theorem 2.2 implies that the stabilization problem for the system(5) can be divided into two sub problems .First, given the target dynamical system $\dot{\xi} = \alpha(\xi)$ which is locally asymptotically stable and of dimension strictly smaller than the dimension of x , find if possible ,a manifold

M described implicitly by $\{x \in \mathbb{R}^n \mid \phi(x) = 0\}$ and in parameterized form by $\{x \in \mathbb{R}^n \mid x = \pi(\xi), \text{ for some } \xi \in \mathbb{R}^p\}$, which can be rendered invariant and such that the restriction of the closed-loop system to M is described by the target dynamics. The mapping $\pi: \xi \rightarrow x$ is an immersion, that is, the rank of π is equal to the dimension of ξ . Secondly design a control law $u = \psi(x, z)$ that drives to zero the off-manifold coordinate $z = \phi(x)$ and keeps the system trajectories bounded.

III. TRANSIENT STABILIZATION OF THE SMIB SYSTEM AND A COMPARISON STUDY

In this section we initially present the modelling of SMIB system and control objective. Next, we synthesize three control laws and performance of these control laws are compared, in the case of machine operating at lightly loaded and heavily loaded conditions.

A. Modelling and Problem Formulation:

Consider the SMIB system with a CSC as shown in Figure 1. It consists of a synchronous generator connected to the infinite bus or reference bus. The magnitude of the voltage and the frequency for the infinite bus are assumed to be constant. In Figure 1 the generator bus is numbered as 1 and the infinite bus as 2. They are connected to each other through a series combination of the line reactance X_{12} and a CSC which is denoted by a reactance $-jX_c$. We use the following.

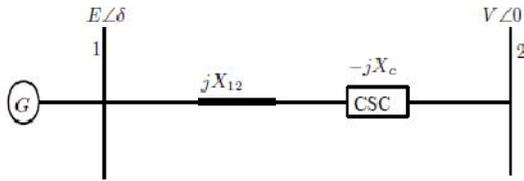


Fig 1. The SMIB system with a CSC

notation: δ is the rotor angle and ω is the rotor angular speed deviation with respect to a synchronously rotating reference for the generator. Let $D > 0$, $M > 0$ and $P > 0$ be the damping constant, moment of inertia constant and the mechanical power input to the generator, respectively. The dynamics of the synchronous generator is described by the swing equation model as,

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} x_2 \\ \frac{1}{M}[P - Dx_2 - b_1 \sin x_1] \end{pmatrix} + \begin{pmatrix} 0 \\ \frac{b_1}{M} \sin x_1 \end{pmatrix} u \quad (12)$$

where $x_1 = \delta$ and $x_2 = \omega$ are the state variables, u is the input to the CSC, x_{1*} is the open loop reactance between buses 1 and 2, and $b_1 = \frac{EV}{x_{1*}}$. We assume that the domain of operation as follows

$$D = \{(x_1, x_2) \in S^1 \times \mathbb{R}^1 \mid d_1 < x_1 < \frac{\pi}{2} - d_1, d_1 > 0\}.$$

1) Control Objective:

The open loop operating equilibrium point for the system (12) is given by $x_* = (x_{1*}, 0)$. We assume that x_* is known to us and synthesize a control law u in order to make the system (12) asymptotically stable at x_* .

B. Controller Synthesis:

The control law are derived using a linear control technique called power system stabilizer, and two nonlinear control technique: Immersion and invariance(I&I)and feedback linearization

1) Linear controller: Power System Stabilizer:

Consider the SMIB system with a CSC as shown in figure1.

Let, the system be $\dot{x} = f(x, u)$. Linearization of the system about the equilibrium point $x = x_*$ and $u = 0$ results in a linear system $\dot{x} = Ax + Bu$, where

$$A = \frac{\partial f}{\partial x}(x, u) \mid x = x_*, u = 0$$

$$B = \frac{\partial f}{\partial u}(x, u) \mid x = x_*, u = 0$$

The liberalized system for (12) is given by

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ \frac{b_1}{M} \cos x_{1*} & -\frac{D}{M} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} 0 \\ -\frac{b_1}{M} \sin x_{1*} \end{pmatrix} u$$

We consider the rotor speed deviation (x_2) as the control signal for the power system stabilizer. Hence, the control input to the system is given by

$$u = -l \frac{1+T_1s}{1+T_2s} x_2 \quad (13)$$

where l , T_1 and T_2 are the tuning parameters which are to be chosen from the phase compensation technique. From (13), we get the controller of the form

$$u = l \frac{1}{sT_2} x_2 + l \frac{T_1}{T_2} x_2 - \frac{1}{sT_2} u. \quad (14)$$

The power system stabilizer is designed for the liberalized system about an equilibrium point by placing the poles at the desired location. So when the controller is applied to the original nonlinear system, the effectiveness of the controller to stabilize the system may be degraded.

2) Controller Synthesis Using Feedback Linearization:

Feed-back linearization cancels out the nonlinear terms in the system model. Using the feedback linearization

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technique, we compute the control law for the system (12) as

$$u = \frac{M}{b_1 \sin x_1} \left(\frac{P}{M} - \frac{b_1 \sin x_1}{M} - \frac{D}{M} x_2 - v \right) \quad (15)$$

where we choose v as

$$v = k_1(x_1 - x_{1*}) + k_2 x_2.$$

The values of the tuning parameters k_1 and k_2 of the controller are determined by using the pole placement technique. The control law is derived to cancel out all the nonlinear terms in system model in ideal case. If any changes in system parameters such as line reactance, then the control law does not cancel out the nonlinearity completely, and this may lead to ineffectiveness of the controller.

3) Controller Synthesis Using (I&I) Technique:

As a first step in the controller synthesis we define a one dimensional target dynamical system as follows

$$\dot{\xi} = -\beta \sin \xi, \beta > 0 \quad (16)$$

With the stable equilibrium point ξ_* , where $\dot{\xi} = \xi - \xi_*$

Once we define the target dynamics, we define a mapping

$\pi: s^1 \rightarrow s^1 \times \mathbb{R}^1$ as follows

$$\pi(\xi) = \begin{pmatrix} \xi \\ \pi_2(\xi) \end{pmatrix}$$

where $\Pi_2(\xi)$ is to be chosen. Then, with this choice of $\Pi(\xi)$ and the target dynamics (16), we get the control law as follows

$$u = \frac{(P - D x_2 - b_1 \sin x_1) + \beta M \cos x_1 x_2 + M \gamma (x_2 + \beta \sin x_1)}{b_1 \sin x_1} \quad (17)$$

where β and γ are the tuning parameters. Note that, as x_1 approaches to zero, the magnitude of the control law grows unbounded.

C. Simulation Results:

We assume the following simulation parameters for the SMIB system as shown figure $M = \frac{8}{100\pi}$, $D = \frac{0.4}{100\pi}$, $E = V = 1$ (pu), $b_1 = 2.5$ (pu), $\frac{1}{3} \leq u \leq 1$. To assess the performance of the proposed control laws we assume that a short circuit fault at the far end of the transmission line at the time $t=1$ s for a duration of 0.1 s

1). Lightly loaded condition:

We use the following system parameters for the lightly loaded condition: The operating equilibrium point is $x_* = (0.4556, 0)$ and $P = 1.1$ (p.u). The values of the tuning parameters are chosen as $\beta = 6.5$ and $\gamma = 9$ for the I&I control law, $k_1 = -29$ and $k_2 = -10$ for the feedback linearization control law, and $l = 1$, $T_1 = 0.082$ and $T_2 = 0.139$ for the power system stabilizer, respectively. From the simulations, we can observe the following: The open loop system exhibits heavy and sustained oscillations in

x_1 and x_2 as shown by dotted lines in Figure 2. The closed-loop system oscillations decay at a faster rate and settle quickly in all the three control strategies. Further, we can observe that, in the case of feedback linearization and power system stabilizer, the controller operates at actuator limits for a short duration, which is not in case of I&I, as shown in Figure 2.

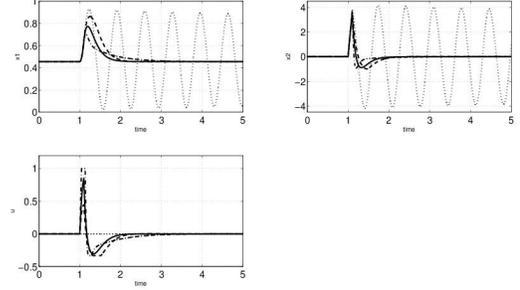


Fig. 2. Response of the SMIB system with a CSC: Solid line (I&I control law), dashed line (feedback linearization) dashed-dot (power system stabilizer), dotted line (open loop response).

2) Heavily Loaded Condition:

We use the following system parameters for the heavily loaded condition. The operating condition equilibrium point is $x_* = (1.5, 0)$ and $P = 2.4937$ (pu). The value of the tuning parameters are chosen as $\beta = 6.5$ and $\gamma = 9$ for the I&I and control law, $k_1 = -29$ and $k_2 = -10$ for feedback linearization control law, and $l = 1$, $T_1 = 0.1961$ and $T_2 = 0.7543$ for the power system stabilizer respectively. It can be seen from figure 3 that, when the machine operated at heavily loaded condition, I&I is working effectively, whereas feedback linearization and power system stabilizer fail to stabilize the closed loop system. Hence we can conclude that performance of the I&I controller is superior to the other two control laws.

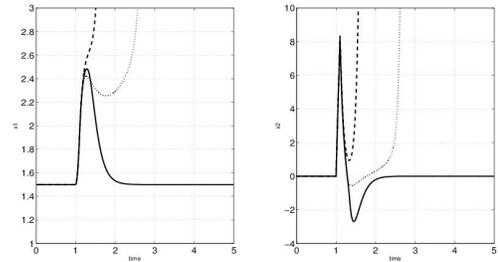


Fig 3 Response of the SMIB system with a CSC: Solid line (I&I) control law), dashed line (feedback linearization) dotted line (power system stabilizer)

In this paper we presented a linear control technique based on power system stabilizer, and nonlinear control laws based on feedback linearization, and Immersion and Invariance methodology to asymptotically stabilize the SMIB with CSCs at equilibrium. The SMIB systems were modeled using the swing equation model. By observing the simulation results, the performance of the I&I control

law, guarantees satisfactory performance even for the heavily loaded condition compared to the other two control technique.

IV. TRANSIENT STABILIZATION OF THE TMIB SYSTEM AND A COMPARISON STUDY

In this section we initially present the modelling of TMIB system and control objective. Next, we derive stabilizing control laws for the TMIB system using power system stabilizer, feedback linearization and I&I techniques. Performance of these control laws are compared, in the case of machine operating at lightly loaded and heavily loaded conditions

A. Modelling and problem formulation:

Consider the TMIB system with two CSCs as shown in Figure 4. It shows two generators G1 and G2 connected with the infinite bus. The generator buses for G1 and G2 are denoted by 1 and 2, respectively, and the infinite bus is denoted by 3. We can write the dynamics of the i-th generator (for i=1,2)

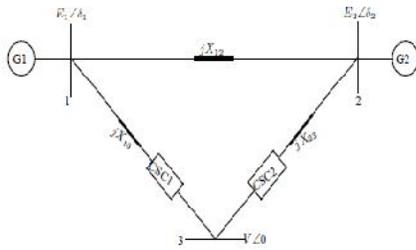


Fig4. A Two Machine Infinite Bus System With 2 CSC's

having δ_i as rotor angles and ω_i as rotor angular speed deviations as follow

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{pmatrix} = \begin{pmatrix} x_3 \\ x_4 \\ \frac{1}{M_1} [P_1 - b_{12} \sin(x_1 - x_2) - b_1 \sin x_1 - D_1 x_3] \\ \frac{1}{M_2} [P_2 - b_{12} \sin(x_2 - x_1) - b_2 \sin x_2 - D_2 x_4] \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ -\frac{b_1}{M_1} \sin x_1 & 0 \\ 0 & -\frac{b_2}{M_2} \sin x_2 \end{pmatrix} \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} \quad (18)$$

where $x_1=\delta_1, x_2 =\delta_2, x_3=\omega_1,$ and $x_4=\omega_2$ are the state variables u_1 and u_2 are the inputs to the CSC and $D_i>0, M_i>0, b_i>0$ and $b_{12} >0$ are the system constants for $i=1,2$. We assume the domain of operation as follows

$$D=\{(x_1, x_2, x_3, x_4) \in S^1 \times S^1 \times \mathbb{R}^2 \mid d_i < x_i < \frac{\pi}{2} - d_i, d_i > 0, i = 1,2\}$$

1) Control Objective:

The open loop operating equilibrium point for the system (18) is given by $x_* = (x_{1*}, x_{2*}, 0, 0)$. We assume that x_* is known to us and synthesize a control laws u_1 and u_2 in order to make the system (18) asymptotically stable at x_* .

B. Controller synthesis:

The control laws are derived using a linear control technique called power system stabilizer and two non linear control techniques: Immersion and invariance (I&I) and Feedback linearization.

1) Linear Controller: Power System Stabilizer:

Consider the TMIB system with two CSC's as shown in figure(4). We consider the rotor speed deviation of generators G1(x_3) and G2(x_4) as the control signals for the power system stabilizer .Hence ,the control inputs to the system are given by

$$u_1 = l_1 \frac{1+T_1s}{1+T_2s} x_3 \quad (19)$$

$$u_2 = l_2 \frac{1+T_3s}{1+T_4s} x_4 \quad (20)$$

where l_1, l_2, T_1, T_2, T_3 and T_4 are the tuning parameters which are to be chosen from phase compensation technique. From (19) and (20), we get the controller of the form

$$u_1 = l_1 \frac{1}{T_2s} x_3 + l_1 \frac{T_1}{T_2} x_3 - \frac{1}{T_2s} u_1 \quad (21)$$

$$u_2 = l_2 \frac{1}{T_4s} x_4 + l_2 \frac{T_3}{T_4s} x_4 - \frac{1}{T_4s} u_2. \quad (22)$$

2) Controller synthesis using feedback linearization:

Using the feedback linearization technique, we can compute the control laws for the system (18) as

$$u_1 = \frac{M_1}{b_1 \sin x_1} \left(\frac{P_1}{M_1} - \frac{b_{12}}{M_1} \sin(x_1 - x_2) - \frac{b_1}{M_1} \sin x_3 - \frac{D_1}{M_1} x_3 + v_1 \right) \quad (23)$$

$$u_2 = \frac{M_2}{b_2 \sin x_2} \left(\frac{P_2}{M_2} + \frac{b_{12}}{M_2} \sin(x_1 - x_2) - \frac{b_2}{M_2} \sin x_2 - \frac{D_2}{M_2} x_4 + v_2 \right) \quad (24)$$

where we choose $v_1 = k_1(x_1 - x_{1*}) + k_3 x_3$ and $v_2 = k_2(x_2 - x_{2*}) + k_4 x_4$. The values of the parameters k_1, k_2, k_3 and k_4 of the controller determined by using pole placement technique.

3) Controller Synthesis using I&I technique:

We define the target dynamical system as follows

$$\dot{\xi}_1 = -\beta_1 \sin \xi_1, \beta_1 > 0 \quad (25)$$

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$$\dot{\xi}_2 = -\beta_2 \sin \xi_2, \beta_2 > 0 \quad (26)$$

with stable equilibrium point $\xi_* = (\xi_{1*}, \xi_{2*})$, where $\xi_* = (\xi_i - \xi_{i*})$ for $i=1,2$.

Once we define the target dynamics, we define a mapping $\Pi: S^1 \times S^1 \rightarrow S^1 \times S^1 \times \mathbb{R}^2$ as follows

$$\Pi(\xi) = \begin{pmatrix} \xi_1 \\ \xi_2 \\ \Pi_3(\xi) \\ \Pi_4(\xi) \end{pmatrix}$$

where $\Pi_3(\xi)$ and $\Pi_4(\xi)$ are to be chosen. Then, with this choice of $\Pi(\xi)$ and the target dynamics (25) and (26), we get the control laws as follows

$$u_1 = \frac{1}{b_1 \sin x_1} [P_1 - b_{12} \sin(x_1 - x_2) - b_1 \sin x_1 - D_1 x_3 + \beta_1 M_1 \cos \bar{x}_1 x_3 + M_1 \gamma_1 (x_3 + \beta_2 \sin x_2)] \quad (27)$$

$$u_2 = \frac{1}{b_2 \sin x_2} [P_2 - b_{12} \sin(x_2 - x_1) - b_2 \sin x_2 - D_2 x_4 + \beta_2 M_2 \cos \bar{x}_2 x_4 + M_2 \gamma_2 (x_4 + \beta_2 \sin x_2)] \quad (28)$$

where $\beta_1, \beta_2, \gamma_1$, and γ_2 are the tuning parameters. Note that as x_1 and x_2 approaches to zero, the magnitude of the control laws grows unbounded.

C. Simulation results

We use the following system parameters for the TMIB

system shown in figure(4): $M_1 = M_2 = \frac{8}{100\pi}, D_1 = D_2 = \frac{0.4}{100\pi}, b_1 = b_2 = 2(\text{pu}), v=1(\text{pu}), \frac{1}{3} \leq u_1 \leq 1, \frac{1}{3} \leq u_2 \leq 1$.

To assess the performance of the proposed control laws we assume that simultaneous faults occurs at the generators G1 and G2, at time $t = 1$ s for a duration of 0.1 s.

1) Lightly loaded condition:

We use the following system parameters for the lightly loaded condition: The operating equilibrium point is $x^* = (0.7447, 0.807, 0, 0)$, $P_1 = 1.2$ (pu) and $P_2 = 1.6$ (pu). The values of the tuning parameters are chosen as $\beta_1 = 6, \beta_2 = 6, \gamma_1 = 9$ and $\gamma_2 = 9$ for the I&I control law $k_1 = -30, k_2 = -10, k_3 = -20$ and $k_4 = -5$ for the feedback linearization control law, and $I_1 = 1, I_2 = 1, T_1 = 2.4, T_2 = 6.5, T_3 = 1.8072$ and $T_4 = 9.7687$ for the power system stabilizer, respectively.

From the simulations, we can observe the following: The open loop system exhibits heavy and sustained oscillations in x_1, x_2, x_3 , and x_4 as shown by dotted lines in figure 5. The closed loop system oscillations decay faster rate and settle quickly in all three control strategies as shown in figure 5.

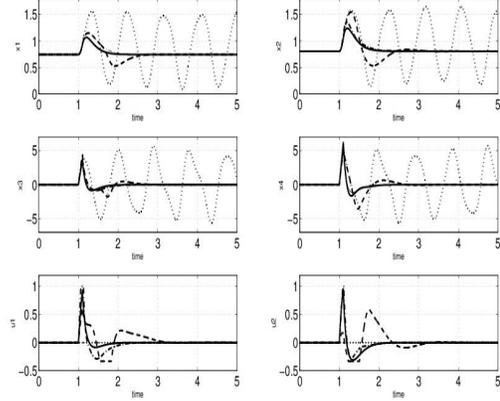


Fig. 5. Response of the TMIB system: Solid line (I&I control law), dashed line (feedback linearization), dashed-dot (power system stabilizer), dotted line (open loop response).

2) Heavily Loaded condition:

We use the following system parameters for the heavily loaded condition: The operating equilibrium point is $x^* = (1.4303, 1.4828, 0, 0)$, $P_1 = 1.8494$ (pu) and $P_2 = 2.1232$ (pu). The values of the tuning parameters are chosen as $\beta_1 = 6, \beta_2 = 6, \gamma_1 = 9$ and $\gamma_2 = 9$ for the I&I control law, $k_1 = -30, k_2 = -10, k_3 = -20$ and $k_4 = -5$ for the feedback linearization control law, and $I_1 = 1, I_2 = 1, T_1 = 0.0644, T_2 = 0.1432, T_3 = 0.0655$ and $T_4 = 0.2773$ for the power system stabilizer, respectively. It can be seen from Figure 6 that, when the machine operating at heavily loaded condition, I&I is working effectively, whereas feedback linearization and power system stabilizer fail to stabilize the closed-loop system. Hence we can conclude that, the performance of the I&I controller is superior.

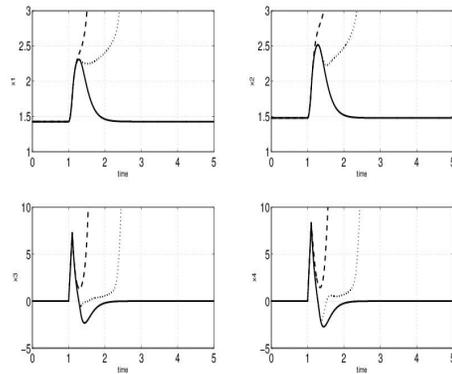


Fig. 6. Response of the TMIB system: Solid line (I&I control law), dashed line (feedback linearization), dotted line (power system stabilizer).

V. CONCLUSION

In this paper we presented a linear control technique based on power system stabilizer, and nonlinear control laws based on feedback linearization, and Immersion and

Invariance methodology to asymptotically stabilize the SMIB and TMIB systems with CSCs at an equilibrium. The SMIB and TMIB systems were modelled using the swing equation model and the CSCs were modelled by the injection model. By observing the simulation results, the performance of the I&I control law, guarantees satisfactory performance even for the heavily loaded condition compared to the other two control techniques.

REFERENCES

- [1] D. S. Kirschen, R. Bacher, and G. T. Heydt, "Special issue on the technology of power system competition," *Proceedings of the IEEE*, vol. 88, pp. 123–127, February 2000.
- [2] Q. Lu and Y. Z. Sun, "Nonlinear stabilizing control of multimachine systems," *IEEE Trans. on Power Systems*, vol. 4, pp.236–241, February 1989.
- [3] J. W. Chapman, M. D. Ilic, C. A. King, L. Eng, and H. Kaufman, "Stabilizing a multimachine power system via decentralized feedback linearizing excitation control," *IEEE Trans. on Power Systems*, vol. 8, pp. 830–839, August 1993.
- [4] Y. Wang, D. J. Hill, R. H. Middleton, and L. Gao, "Transient stability enhancement and voltage regulation of power systems," *IEEE Trans. on Power Systems*, vol. 8, pp. 620–627, May 1993.
- [5] C. A. King, J. W. Chapman, and M. D. Ilic, "Feedback linearizing excitation control on a full-scale power system model," *IEEE Trans. on Power Systems*, vol. 9, pp. 1102–1109, May 1994.
- [6] W. Mielczarski and A. M. Zajaczkowski, "Nonlinear field voltage control of a synchronous generator using feedback linearization," *Automatica*, vol. 30, pp. 1625–1630, October 1994.
- [7] X. Y. Li, "Nonlinear controller design of thyristor controlled series compensation for damping inter-area power oscillations," *Electric Power Systems Research*, vol. 76, pp. 1040–1046, August 2006.
- [8] M. Ghandhari, G. Andersson, and I. A. Hiskens, "Control Lyapunov functions for controllable series devices," *IEEE Trans. on Power Systems*, vol. 16, pp. 689–694, November 2001.
- [9] M. Ghandhari, *Control Lyapunov Functions: A Control Strategy for Damping of Power Oscillations in Large Power Systems*. PhD thesis, KTH, Bonn, Germany, 2000.
- [10] N. S. Manjarekar, R. N. Banavar, and R. Ortega, "Application of Passivity-based Control to Stabilization of the SMIB System with Controllable Series Devices," in *Proceedings of IFAC*, (Seoul), pp. 5581–5586, 2008.
- [11] N. S. Manjarekar, R. N. Banavar, and R. Ortega, "Nonlinear Control Synthesis for Asymptotic Stabilization of the Swing Equation using a Controllable Series Capacitor via Immersion and Invariance," in *IEEE Conference on Decision & Control*, (Cancun, Mexico), pp. 2493–2498, 2008.
- [12] M. Ghandhari, G. Andersson, M. Pavella, and D. Ernst, "A control strategy for controllable series capacitor in electric power system"- *Conference on Decision & Control*, (Cancun, Mexico), pp. 2493–2498, 2008
- [13] K. R. Padiyar, *Power System Dynamics: Stability and Control*. Hyderabad: BS Publications, 2002.
- [14] H. K. Khalil, *Nonlinear System*. Prentice Hall, 2002.
- [15] A. Astolfi and R. Ortega, "Immersion and Invariance: A New Tool for Stabilization and Adaptive Control of Nonlinear Systems," *IEEE Trans. on Automatic Control*, vol. 48, pp. 590–606, April 2003.
- [16] A. Astolfi and R. Ortega, "Invariant manifolds, asymptotic immersion and the (adaptive) stabilization of nonlinear systems," in *Nonlinear and Adaptive Control* (A. Zinober and D. Owens, eds.), vol. 281 of *Lecture Notes in Control and Information Sciences*, pp. 1–20, Springer, 2003.
- [17] D. Karagiannis, R. Ortega, and A. Astolfi, "Nonlinear adaptive stabilization via system immersion: Control design and applications," in *Advanced Topics in Control Systems Theory* (F. Lamnabhi-Lagarigue, A. Loria, and E. Panteley, eds.), vol. 311 of *Lecture Notes in Control and Information Sciences*, pp. 1–21, Springer, 2005.
- [18] J. A. Acosta, R. Ortega, A. Astolfi, and I. Sarras, "A constructive solution for stabilization via immersion and invariance: The cart and pendulum system," *Automatica*, vol. 44, no. 9, pp. 2352–2357, 2008.
- [19] P. Kundur, *Power System Stability and Control*. New York: McGraw-Hill, 1994.