FACTS Controllers for Power-System Modelling and Immersion and Invariance as stabilization technique

PROJECT REPORT

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by

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Introduction

This project revolves around recognising what power systems in essence are and how they operate briefly. Modeling of basic power systems and power flow equations are also dealt with. While power systems in indeed relevant to the scope of this project, a more control system view point is what is discussed. This is so because the aim is to understand the need of control and studying some controllers that exist in today's world for doing the same.

The second part of this project deals with understanding Immersion and Invariance as a control technique for control of power systems. This an extremely mathematical procedure and therefore some basic definitions are discussed.

Finally, after studying $I\&$ for a basic model an extension is proposed in order to implement to a larger and a more realistic system.

List of Figures

1 Power Systems

A power system in the most simplest terms is a network of electrical devices connected together used for a general transfer or exchange of electrical power. The most common example of an electrical power system is that of a power grid that allows a provision of power to areas. An electrical grid can be roughly divided into sets of generators that supply power and the transmission systems that carry this power. In an attempt to understand complex power systems we first take a look at the simple Single Machine Infinite Bus system and some of its characteristics.

1.1 Single Machine Infinite Bus System- Swing Equation

The single machine infinite bus system is a representation of a kind of real power system where one generator and a group of generators are connected by transmission lines to large networks.
Before we can jump into the details of what the SMIB entails we need to understand what an infinite bus is. An infinite bus is one where the voltage and frequence at the bus remains constant. This essentially means that any irrespective of the system connected to the infinite us it doesn't matter much with respect to the operating view point. We now procees to discuss the classical model of the SMIB.

1.1.1 Mathematical Model

We go over a few assumptions and notes before we describe the classical mathematical model.

1. The field current is assumed to be constant so that the generator stator induced voltage is constant.
2. The effect of rotor windings is neglected.
3. Input mechanical power is assumed to be constant for the period relevant to us.
4. Generator is assumed to be of cylindrical type rotor.
5. $E\angle\delta$ Complex Internal Voltage of synchronous Generator behind the transient reactance X'_d
6. $V_T\angle\theta_T$ denotes the terminal voltage of the synchronous generator
7. X_T and X_L denote the Transformer and Line Reactance respectively.
8. $V_\infty\angle 0$ is the complex infinite bus voltage
9. P_m and P_e are the mechanical and electrical power
10. H is the inertia constant of the generator and M is called the angular momentum
11. H_∞ is the inertia constant of the grid on the infinite bus
12. δ is called the load angle and S_B is the Base MVA

Electrical Classical Model of the swing equation

$P_e = \frac{EV_\infty}{X'_d + X_T + X_L} \times sin(\delta)$

$P_{max} = \frac{EV_\infty}{X'_d + X_T + X_L}$ at $\delta = 90$ degrees.

This means essentially $P_e = P_{max} sin(\delta)$

The swing equation is now as follows:

$$M\frac{d^2\delta}{dt^2} = P_s - P_{max}sin(\delta)$$

Now we make some modifications to the swing equation and introduce the Inertia constant.

$\frac{d\delta_m}{dt} = w_m - w_{ms}$, where w_{ms} is the synchronous speed of the generator. $M = Jw_m$ and using this we can write the equation as

$$Jw_m\frac{d^2\delta_m}{dt^2} = P_s - P_{max}sin(\delta_m)$$

$$\frac{Jw_m w_{ms}}{S_B}\frac{d^2\delta_m}{dt^2} = \frac{w_{ms}}{2}(\frac{P_s}{S_B} - \frac{P_{max}sin(\delta_m)}{S_B})$$

We now define H as follows, under the assumption that $w_m \approx w_{ms}$:

$$H = \frac{\frac{1}{2}Jw_{ms}^2}{S_B}$$

We further note that δ_m and w_{ms} are expressed in mechanical radians per second. Converting it to electrical radians per second we have : $\delta = \frac{p}{2}\delta_m$ and $w_s = \frac{p}{2}w_{ms}$

The most simplified swing equation based on all these observations is the one we look to implement usually and is stated below:

$$\frac{d^2\delta}{dt^2} = \frac{w_s}{2H}(P_s - P_{max}sin(\delta))$$

per unit.

1.1.2 Simulink Implementation and Simulation

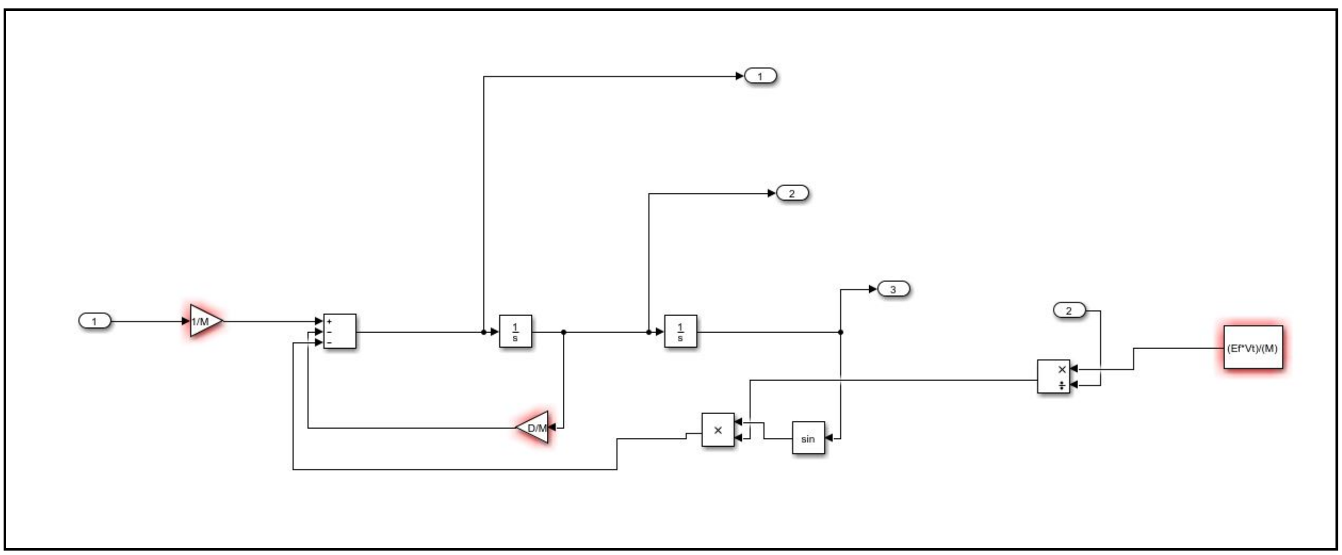

Figure 1: SMIB Simulink Model

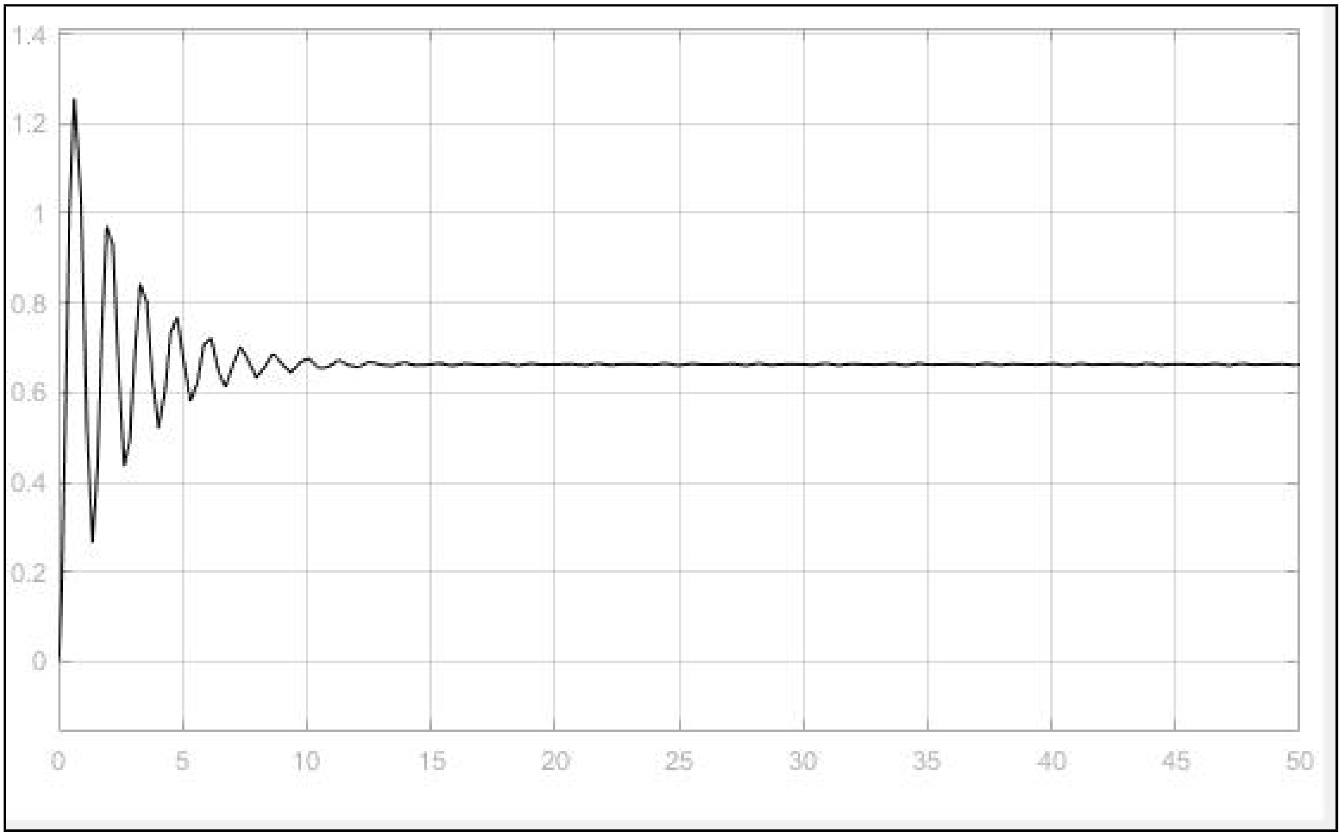

Figure 2: Load angle dynamics of SMIB

1.2 Centre of Inertia(COI)

In the case of a multimachine system we resort to using a concept called centre of inertia to find the effective inertia of the system. The process of obtaining the Centre of Inertia. the analysis for this as follows:

$$\frac{d(w_i - w_0)}{dt} = \frac{dw_i}{dt} = \frac{w_B}{2H_i}(T_{m_i} - T_{e_i})$$

Here, w_i denotes the rotor speed of the i^{th} machine and w_0 is the rated speed of the machines. T_{m_i} andT_{e_i} denote the mechanical and electrical torque of each machine respectively. w_B is the base frequency and H_i is the inertia constant for each machine.
Now let us say we have n machines and we want to find the effective Inertia constant. We first sum up the n swing equations.

$$\sum_{i=1}^{n} \frac{2H_i}{w_B} \frac{dw_i}{dt} = \sum_{i=1}^{n} (T_{m_i} - T_{e_i})$$

We assume frequency deviations to be small and therefore we can say that $(T_{m_i} - T_{e_i}) \approx (P_{m_i} - P_{e_i})$
We also note here that $\sum_{i=1}^{n} P_{e_i} = \sum_{i=1}^{k} P_{L_k}$(total load on the system) + losses
Using these simplifying assumptions we have that

$$\sum_{i=1}^{n} \frac{2H_i}{w_B} \frac{dw_i}{dt} = \sum_{i=1}^{n} P_{m_i} - \sum_{i=1}^{k} P_{L_k} - losses$$

Now we take just the LHS of the above equation and rearrange the terms a bit

$$\sum_{i=1}^{n} \frac{2H_i}{w_B} \frac{dw_i}{dt} = 2\frac{\sum_{i=1}^{n} H_i}{w_B} \frac{d(\frac{\sum_{i=1}^{n} H_i w_i}{\sum_{i=1}^{n} H_i})}{dt} = 2\frac{H_{coi}}{w_B} \frac{dw_{coi}}{dt}$$

2 Need for Control in Power Systems

We saw in the graph of the SMIB load angle that there are oscillations of the load angle while they do die out can still cause huge power flow and cause issues. We therefore recognise the need to use a controller to dampen the oscillations as soon as possible rather than allow it to die out eventually. So this system although nominally stable still can make use of a controller. There exist various controllers and control techniques to device controllers to help with the damping of the load angle oscillations. The use of FACTS(Flexible AC Transmission System) Controllers are a very nice way to achieve this damping.

2.1 Flexible AC Transmission Line System Controllers

These are devices based on thyristors which are mainly used to ensure power system reliability by using some control objecttives and further these devices also help stability.

2.1.1 Thyristors

Like the diode, the thyristor is unidirectional device, in that it can conduct only in one direction. The way in which it differs from the diode is the it can made to operate as either an open circuit or a diode based on how the thyristor gate is triggered.
Based on thyristors there are many controllers some of which are series controllers and some are shunt controllers. We can use both for the SMIB dynamics.

2.1.2 Static VAR Compensator(SVC)

The SVC is modelled by a shunt variable admittance which can be placed either at the terminal bus of a transmission line or in the middle of a long line. The SVC is a shunt FACTS controller that is capable of exchange of capacitive or inductive current with the power system so as to help maintain stability.

2.1.3 Thyristor Controlled Series Compensation

TCSCs are used in power systems to dynamically control the reactance of transmission lines in order to provide sufficient load compensation. The benefits of TCSC are seen in its ability to control the amount of compensation of a transmission line, and in its ability to operate in different modes. These traits are very desirable since loads are constantly changing and cannot always be predicted.

TCSC designs operate in the same way as Fixed Series Compensation, but provide variable control of the reactance absorbed by the capacitor device.

TCSC operates in different modes depending on when the thyristors for the inductive branch are triggered. The modes of operation are as listed:

1. Blocking mode: Thyristor valve is always off, opening inductive branch, and effectively causing the TCSC to operate as FSC
2. Bypass mode: Thyristor valve is always on, causing TCSC to operate as capacitor and inductor in parallel, reducing current through TCSC

3. Capacitive boost mode: Forward voltage thyristor valve is triggered slightly before capacitor voltage crosses zero to allow current to flow through inductive branch, adding to capacitive current. This effectively increases the observed capacitance of the TCSC without requiring a larger capacitor within the TCSC.

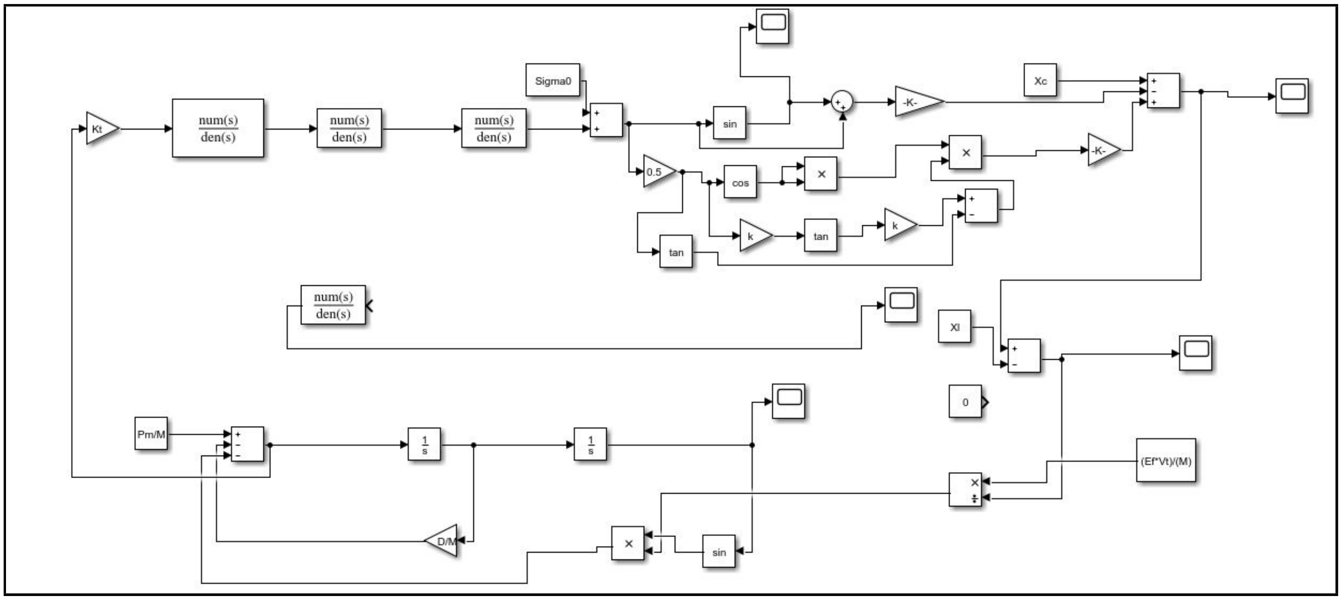

Figure 3: Simulink Implementation of SMIB with TCSC

After implementation of the TCSC in Simulink we observe that the oscillations actually die out quite fast when compare to the scenario without the controller. Having studied [3] in great detail it is actually clear why this happens. This is just one scenario on what to do with a TCSC controller.

It is instructive to note here that another direction for furthering the research in this direction is to play around with the SVC and TCSC and try different combinations of these and see which of those combinations actually leads to a better control strategy.

3 Immersion and Invariance as a Control Technique

3.1 Definitions

1. **Smooth Map**
Let $U \subset \Re^n$ be open. A map $f : U \to \Re^p$ is smooth if partial derivatives of all orders exist and are also continuous.

2. **Diffeomorphism**
If U, $V \subset \Re^n$ are open then $f : U \to V$ is a diffeomorphism if it is smooth and if it's inverse is smooth.

3. **Differentiable Manifold**
In essence a Differentiable Manifold is just a topological space that in the neighbourhood of each of its points looks like an open set of $\Re^k$. A more formal definiton is as follows:
A subset M of $\Re^n$ is a k-dimensional manifold if for each x $\in M$ there exist open sets U and V of $\Re^n$ where x $\in$ U and a diffeomorphism f from U to V such that: $f(U \cap M) = \{\ y \in V | y^{k+1} = ... = y^n = 0\}$

4. **Smooth Manifold**
$M \subset \Re^n$ is a smooth manifold with a dimension m if $\forall$ x $\in M$ there exists a neighbourhood U of x in M, an open set $V \subset \Re^m$ and a diffeomorphism $\Phi : U \to V$. Such maps Φ are in fact called a chart of M around x.
A collection of all charts whose domain spans M is called an Atlas.

5. **Immersion Map**
Let $f : M \to N$ be a smooth map. This map f is said to be an immersion if $d_x f$ is injective.
In other words, when $m \leq n$, the linear map $\Re^m \to \Re^n$ defined by a matrix A is injective if it has a rank m.

6. **Submanifold**
A submanifold of a manifold M is a subset S which itself has a similar structure to that of M. Based on some properties it satisfies under the inclusion map they are classified as Immersed Submanifold and Embedded Submanifold.

7. **Immersed Submanifold**
An immersed submanifold S of a manifold M is the image of the immersion map, such that the immersion map is injective.

8. **Invariant Manifold**
In most simple terms, an invariant manifold is a topological manifold which is unaffected by the action of a dynamical system. Invaraint manifold are usually constructed about an equilibrium point.

3.2 I & I for a Differential Algebraic System

We consider a dynamical system (such that all functions involved are smooth maps) of the form:

$$\dot{x} = f(x, y) + g(x, y)u \tag{1}$$

$$h(x, y) = 0 \tag{2}$$

on a Smooth manifold $\mathcal{L}$ of dimension n+q. We note that f,g and h are the following maps:

$f : \Re^n \times \Re^q \to \Re^n$, $g : \Re^n \times \Re^q \to \Re^{n \times m}$ and $h : \Re^n \times \Re^q \to \Re^q$. We also impose the following condition on h:
Rank$[grad(h_1)\ ....\ grad(h_q)]^T$ = q

This rank condition in fact enforces the immersion condition.

The inspiration to use immersion and invariance is that we don't need our control to force the system to an exact equilibrium immediately. Instead, we try to force the system dynamics to the neighbourhood of the required equilibrium such that the control will asymptotically lead the dynamics to the equilibrium point. This is in fact ensured by the Invariant condition that is imposed. We also make use of an attractive manifold condition to further make the asymptotic convergence actually happen.

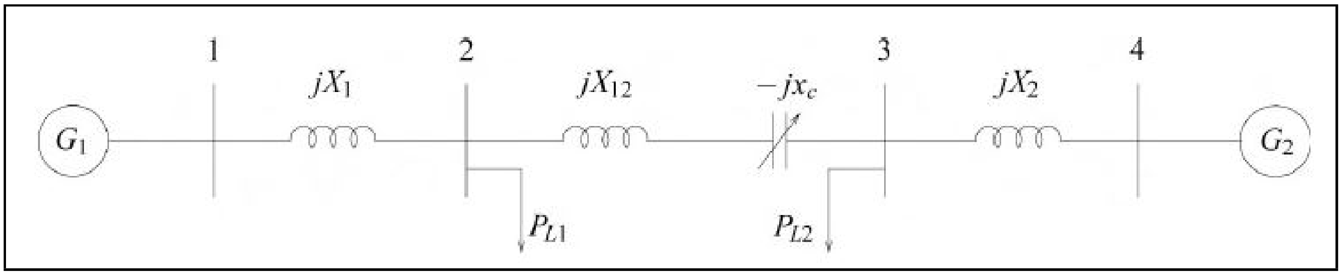

Figure 4: Two machine system with a series variable capacitance

The systematic procedure for $I\&I$ for a DAE has been mentioned quite clearly in [1] and this procedure has been applied to a 2 generator 4 bus system with variable capacitance controller. Having followed the procedure step by step some observations and notes have been taken down. We use the procedure in [1] along with the following observations as a basis to build on $I\&I$ for a 3 machine 8 bus system as discussed in a later section.

1. The target dynamics is decided on the basis of knowing a system that is simple to interpret but still remains within the scope of the dynamics of the required problem.
2. The algebraic equations in the target dynamics can't in fact be dropped. The algebraic equation arises as a result of the uniqueness of maps that we try to derive between the target dynamics and required dynamics.
3. The application of invariance condition to the control law on the manifold in question is what gives rise to the off the manifold control law. This is of particular interest to us because the off the manifold control will force the dynamics onto the manifold in question and force the convergence to the particular equilibrium point we want in due time.
4. Only Real Power power flow equations have been used and reactive power equations have been neglected as an assumption of constant voltage at load buses have been made.

4 Future Scope

Having studied the Single Machine Infinite bus in some detail and then the two-generator system using Immersion and Invariance as a control technique the next logical step is to use this in a practical problem. While the 2 generator system gave us some insight into the use of a control strategy, it isn't a very real-world scenario. In the real world many more generators are connected to each-other. To make a step in that direction we propose the 3generator 6 bus model as the first generalization of the 2 generator model.

4.1 Three Generator 6 bus model

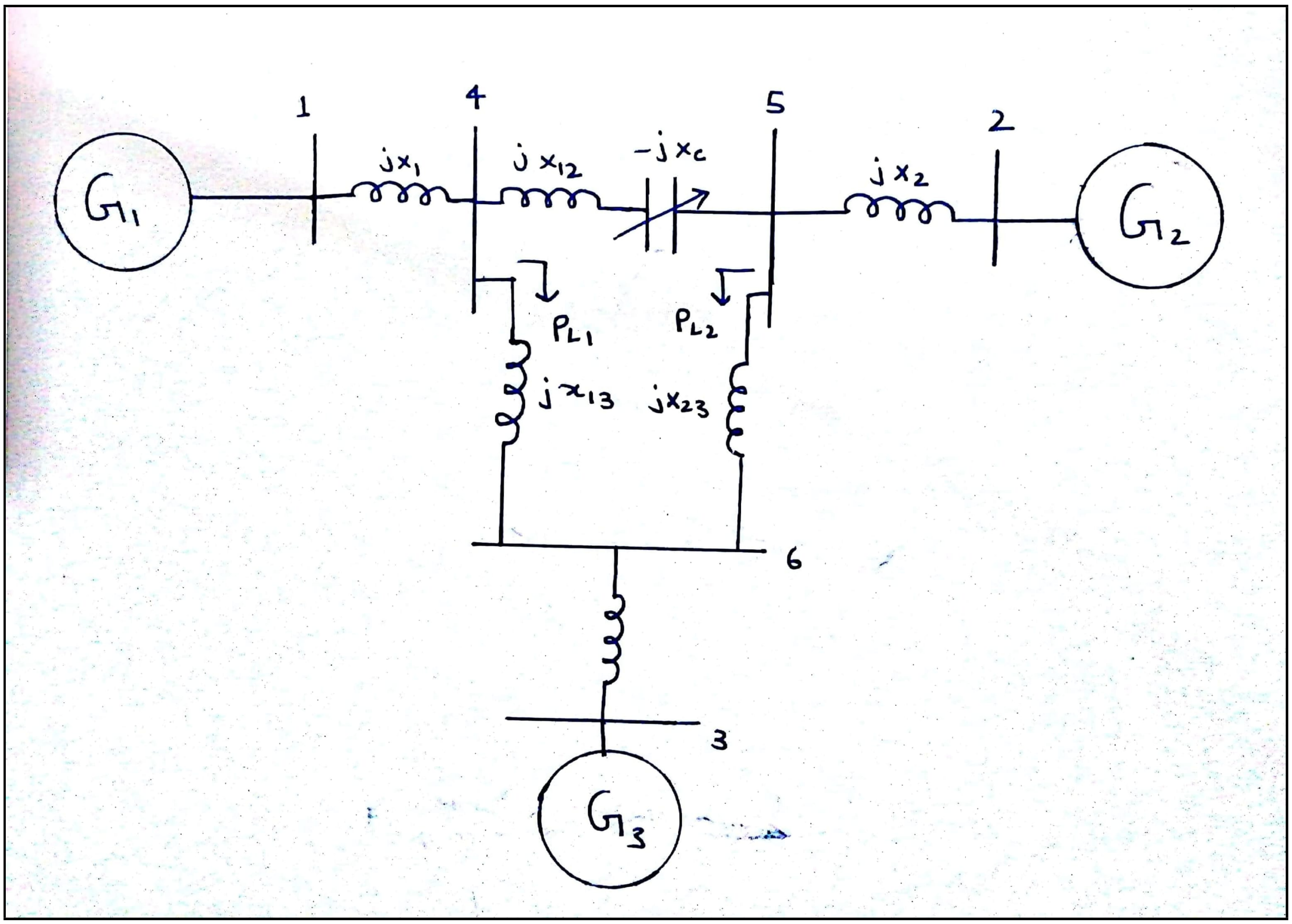

Figure 5: 3 generator 6 bus system with variable capacitance

We propose to apply the method described in the above section and in [1] to analyse $I\&I$ for the 3 machine system. Based on the results from [1] we know that the control law will in fact help the system improve the oscillations and achieve the required goals. But we have a large difference here. There are more transmission lines now and therefore more scope for oscillations. We also observe that maybe in this scale having just one variable capacitance as a controller may not prove all that useful. Still, it is most instructive to start from this basic case to build on it further. The improved along these lines is the best way to go forward.

As a start in this direction we propose the model for the above system:

$\dot{x_1} = x_4$

$\dot{x_2} = x_5$

$\dot{x_3} = x_6$

$\dot{x_4} = \frac{1}{M_1}(P_1 - D_1x_4 - b_1sin(x_1 - y_1))$

$\dot{x_5} = \frac{1}{M_2}(P_2 - D_2x_5 - b_2sin(x_2 - y_2))$

$\dot{x_6} = \frac{1}{M_3}(P_3 - D_3x_6 - b_3sin(x_3 - y_3))$

$\dot{x_7} = \frac{1}{T}(-x_7 + x_7^* + u)$

$b_1sin(x_1 - y_1) - \frac{b_{12}sin(y_1-y_2)}{x_7} - P_{L_1} + \frac{b_{13}sin(y_1-y_3)}{x_7} = 0$

$b_2sin(x_2 - y_2) + \frac{b_{12}sin(y_1-y_2)}{x_7} - P_{L_2} + \frac{b_{23}sin(y_2-y_3)}{x_7} = 0$

$b_3sin(x_1 - y_1) - \frac{b_{13}sin(y_1-y_3)}{x_7} - \frac{b_{23}sin(y_2-y_3)}{x_7} = 0$

The target dynamics can be chosen as follows:

$\dot{\xi_1} = \xi_4$

$\dot{\xi_2} = \xi_5$

$\dot{\xi_3} = \xi_6$

$\dot{\xi_4} = \frac{1}{M_1}(-D_1\xi_4 - b_1sin(\tilde{\xi_1} - y_1))$

$\dot{\xi_5} = \frac{1}{M_2}(-D_2\xi_5 - b_2sin(\tilde{\xi_2} - y_2))$

$\dot{\xi_6} = \frac{1}{M_3}(-D_3\xi_6 - b_3sin(\tilde{\xi_3} - y_3))$

We take the following substitutions:

$\frac{b_i}{M_i} = \beta_i$ for all $i = 1, 2, 3, 4$

On following the procedure of finding the manifold maps such that the Immersion and Invariance principles are followed [1], we get the following necessary algebraic condition in the target system:

$$0 = \beta_1M_1sin(\tilde{\xi_1} - \eta) + \beta_2M_2sin(\tilde{\xi_2} - \eta) + \beta_3M_3sin(\tilde{\xi_3} - \eta)$$

Having obtained the Target system now we need only find the control law on and off the manifold. This is proposed as the further scope of this study oriented project.

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