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Modeling and Simulation of Hybrid Power Flow Controller for Improving the Performance of Power System

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***Abstract*— The demand of electrical energy is rising across the world. But with that, installation of new generation or transmission system is the matters, constrained by economical and environmental factors. The alternative is to utilize the maximum capacity of existing system by some means. FACTS provides avenue to utilize the maximum capacity of existing system without endangering the stability, security, and performance of system, thus providing efficient utilization of existing system. UPFC is the most versatile FACTS device, which have the best performance characteristics in comparison to other classical controllers. But UPFC is very costly controller because of its configuration, consists of two VSCs. And the topology used in UPFC does not allow it to retrofit the existing equipment like switched capacitor, SVC, TCSC etc.**

This paper discusses the applicability of "Hybrid Power Flow Controller" (HPFC) as a cost effective and performance equivalent alternative of UPFC. In this paper, two topologies of HPFC are evaluated. Both topologies consist of a reactive power compensator and two VSCs. UPFC is a FACTS device consisting two converters, one is in series and one is in shunt with the line. In first topology of HPFC, the shunt converter of UPFC is substituted by a (presumably existing) switched capacitor, while its series converter is split into two "half sized" ones, installed on each side of the shunt device. And in second topology of HPFC, one of the switching converters of the UPFC is replaced by thyristor controlled variable impedance and other converter of UPFC is split into two "half sized" ones, installed on each side of the series device. Such topological arrangement results in operating characteristics similar to those of the UPFC, while achieving considerable savings in the total required converter MVA ratings.

The models are designed in MATLAB/SIMULINK. The HPFC principles are explained with results and compared with UPFC to show that HPFC can be regarded as a cost effective and performance equivalent alternative of UPFC.

I. INTRODUCTION

The demand is increasing constantly for electrical energy across the world. But with that, installation of new generation and transmission systems are the matters which are constrained by economical and environmental factors. In most cases due to some reasons (like unavailability of right-of –way and area for transmission and generation system), it is not possible to generate electrical energy at the location where it is going to be consumed. So it is the requirement of power system to transmit power from generating stations (large power generating plants) to the load centers through the transmission system. Electrical energy is generated centrally in bulk amount and transmitted economically with the use of high voltage transmission over a long distance to the consumption point.

To maximize the reliability of electrical supply, to maintain security level of power system and because of some other factors like environment, economic etc, interconnection of transmission systems in various geopolitical and geographic areas is a common practice. Which makes the transmission system very large and complex electrical network, consists of generation and consumption areas in hundreds and transmission lines in thousands. For a complex circuit like transmission system, controlling of power flow through the transmission lines is a complicated problem, next important issue with that complex system is to control the voltage at each bus with other performance parameters of the system.

The invention of thyristor in 1970s provides various possible classical means to control power system. Thyristors are semiconductor devices which can be simply use as an unidirectional switches that starts conduction by providing a proper turn-on pulse (gate signal) between gate and cathode terminal of thyristor. Thyristors stops conduction, when current through anode terminal is brought to zero by some means. Mechanical switches (used in devices to control power system's parameters) were replaced by thyristors to solve the problem of switching cycles in mechanical switched. Application of thyristor includes TSC, TCR and thyristor based phase angle regulator and tap changer. Some more novel circuit configuration have emerged by using the property of thyristor to delay the turn on time. These circuit provides continuous control over compensator parameters, which includes SVC, TCSC.

Technological advancements of semiconductor industry advent a new power grade semiconductor device called gate turn-off thyristor (GTO). GTO has the same functional capability to thyristors but it has the ability by which it can be turned off by simply providing a negative gate current to its gate cathode terminals, which make it more versatile semiconductor device in compare to general thyristor. In mid of 1980s, GTO was commercially available, which made it possible to make large current source or voltage source converter. VSCs can generate voltage with full control over its magnitude and phase. In construction of VSC, one side of

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VSC consists of switching element like GTO and other side it requires a DC capacitor as a means of voltage support.

The "flexible AC transmission system (FACTS) refer to a concept of power flow control through AC transmission lines using static converters". The advent of VSCs provides converter based FACTS controller having higher functional capability, includes the series static synchronous compensators (SSSC), advanced static compensator (STATCOM), interline power flow controller (IPFC), and the most versatile FACTS controller "unified power flow controller (UPFC)".

II. HYBRID POWER FLOW CONTROLLER

A. Topologies used for HPFC

Fig. 2.1 shows the typical application of "hybrid power flow controller", which is installed between two electrical areas connected by a transmission line. As shown in fig. 2.1, HPFC's first topology consists of a the static VAr compensator (SVC) which works as a shunt connected variable susceptance at center and two VSCs connected in series with the transmission line by means of coupling transformers on each side of SVC. The main advantage of the HPFC topology in comparison to other known FACTS controllers like UPFC is that it can be used to retrofit existing equipment. Therefore, the point of installation of HPFC is an important issue and which will often be dictated by the location of existing equipment (usually HPFC is installed at the location already have reactive power compensators like SVC, TCSC etc) and in general it will be at some distance from strong voltage bus within the transmission line. The converters (VSCs) are connected through a common DC link like UPFC. By using the virtue of converters, the magnitude and angle of supplied voltage can be control, by which active power flow and the reactive power exchanged with the line can be simultaneously and independently controlled. The static VAr compensator (SVC) used in topology is coordinated with the control of converters to supply the bulk of total required reactive power.

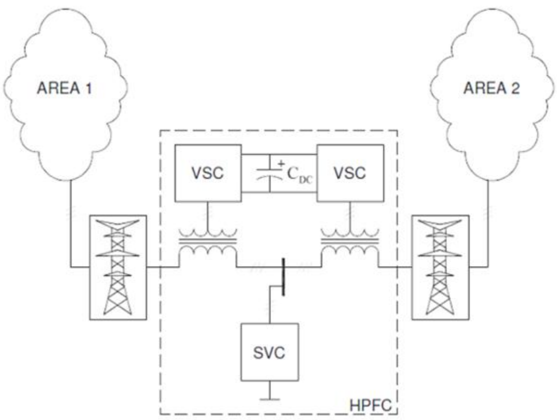

Figure 2.1: Topology-1 for Hybrid Power Flow Controller (HPFC1)

The second topology for HPFC is shown in fig 2.2, which is the dual topology of above topology. With some simple circuit transformations the second topology of HPFC can be obtained. In circuit transformations, let the static VAr compensator (SVC) is replaced by two half sized shunt connected current source converter (CSC). And two series connected voltage sources are combined and replaced by a variable reactance. Similar to first topology, the CSCs are coupled through a common DC link, and hence exchange of active power is possible.

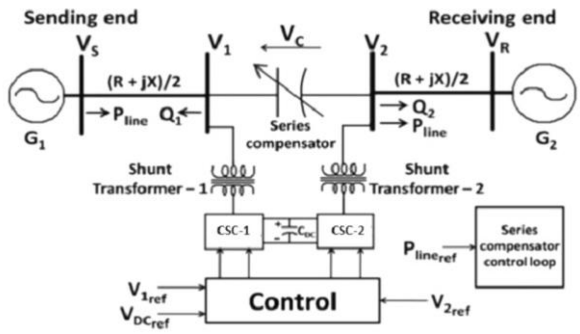

Figure 2.2: Topology-2 for Hybrid Power Flow Controller

Second topology use CSCs in shunt, which offers poor dynamic performance with respect to VSCs. The CSCs offer poor versatility (because it use line commutated converters) when compared VSCs, which require self-commutated converter for their operation. Because of those advantages, in next topology of HPFC, CSCs are replaced by VSCs from second topology.

The third topology for HPFC is shown in fig 2.3. This topology consists of a series compensator (like TCSC) and two VSCs, interconnected through a common DC link like others topology of HPFC and UPFC. The rated capacity of VSC used in this topology is just half of shunt VSC used in UPFC for almost similar performance. In this topology, through coupling transformer VSCs are shunt connected with the transmission line on each side of series compensator (like TCSC).

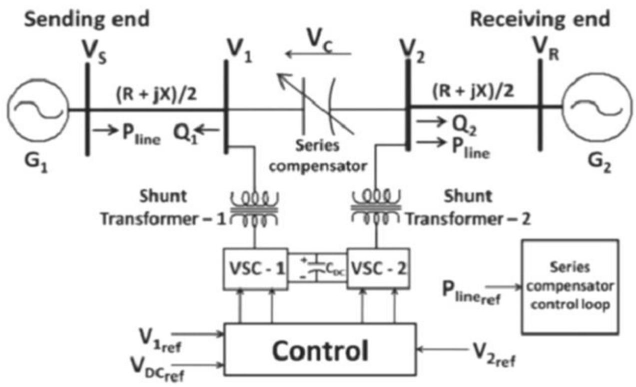

Figure 2.3: Topology-3 for Hybrid Power Flow Controller (HPFC2)

The basic comparison between these topologies of HPFC with the topology used for UPFC gives the important features of new circuit. In brief, the shunt converter used in topology of UPFC is replaced by a classical shunt (SVC) or series (TCSC) compensator, and the series converter used in topology of UPFC is replaced by two half sized converters, which are installed on each side of the classical compensators

(SVC or TCSC). Because of these topologies a considerable saving in total required converters rating is possible, consequently these topologies gives rise to retrofit application.

B. Functional Capability of HPFC

Just like UPFC, HPFC can also independently and simultaneously control the real power and reactive power flow through the transmission line. If HPFC is not installed between two area shown in fig 2.1, the natural power flow through the line is given by:

$$P_O = 3\,\frac{|V_S||V_R|}{X_L}\,\mathrm{Sin}\,\delta \qquad \ldots(2.1)$$

Where,

$|V_S|$ = Magnitude of sending end voltage,
$|V_R|$ = Magnitude of receiving end voltage,
δ = Power angle ($\delta = \delta_S - \delta_R$)

The operating point for the case of natural power flow ($V_X = V_Y = 0$, $B_M = 0$) is shown in fig 2.4

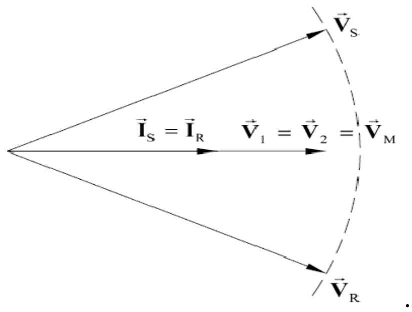

Figure 2.4: HPFC phasor diagram - Operating point for natural power flow

HPFC has the ability to control the power flow through line. To reduce the power flow, HPFC injects voltage (V_X & V_Y) through converters used in circuit configuration, so as to decrease the angle difference between V_S & V_1, and V_2 & V_R, respectively. Operating point for that case is shown in fig 2.5, with the help of phasor representation.

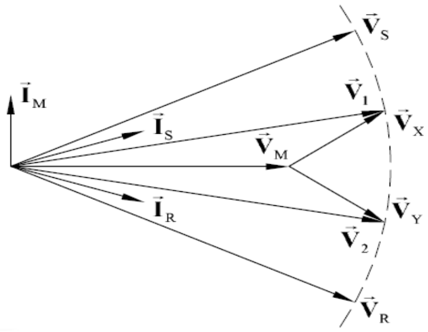

Figure 2.5: HPFC phasor diagram - Operating point for reduced power flow

Now for the same value of line currents, if the value of shunt connected susceptance (B_M) is change so as the magnitude of vector V_M is increased. The operating points for that case is shown in fig 2.6, which shows that, with larger value of V_M, the value of V_X and V_Y are also change.

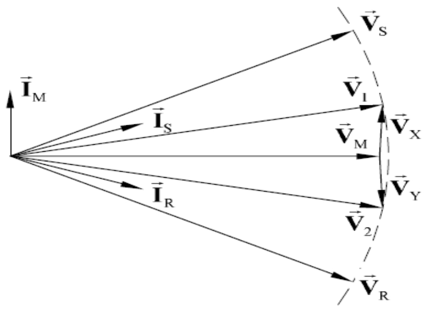

Figure 2.6: HPFC phasor diagram- B_M control reduces converter voltage

The comparison between fig 2.5, and fig 2.6 shows that, the required voltage rating of converters of HPFC can be decrease with a step change in the value of B_M. So, the MVA rating of converters used in HPFC topology is almost half of the converter used in UPFC for similar performance.

The second topology of HPFC explained in previous section, also have the ability to control the active and reactive power flow through the line by injecting a variable voltage (V_C). This topology consists of a series compensator (TCSC) of variable impedance. By varying the impedance (with the help of TCSC), the magnitude of V_C can be controlled. By controlling the exchange of reactive power with the line, HPFC can control the phase angle of injected voltage (V_C). The injected voltage (V_C) is simply define as:

$$V_C = V_2 - V_1 \qquad \ldots(2.2)$$

Therefore phase angle of V_C can be control by controlling the magnitude of V_2 and V_1, which depend on the reactive power output of VSCs. This is shown in fig 2.7

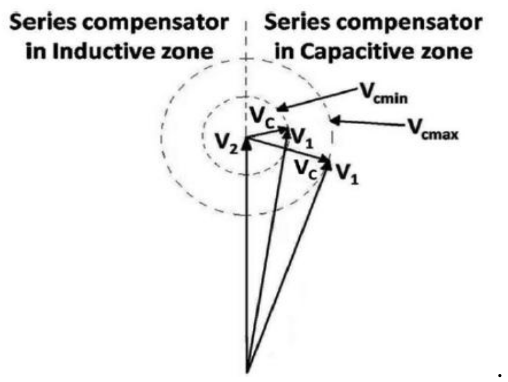

Figure 2.7: Injection of voltage (VC) in series

Where V_{Cmin} and V_{Cmax} are the limits of injected voltage (V_C), controlled by the variable impedance of TCSC.

III. SIMULATION MODEL AND RESULT

The simulation model of two machine system (TMS) without any controller is shown in fig 3.1. The TMS in simulation model consists of two synchronous machines, interconnected through transformers, transmission line and a load of 5000 MW. The detailed data of TMS are given in the Appendix. The power measurement, voltage measurement and machine performance parameter blocks are present in model.

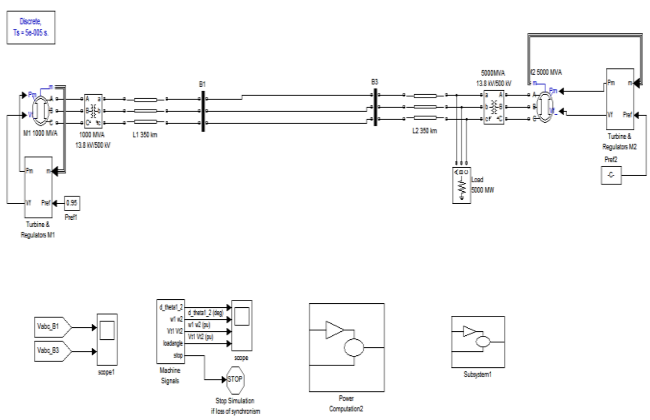

Figure 3.1: Simulation model of TMS without controller

The power flow through the bus B1 or B3, with the help of power measurement block is 928.7 MW and 26.32 MVAr.

The performance parameters of TMS, which includes rotor angle deviation, rotor speed, terminal voltage and load angle for both machines are shown in fig 3.2. Which shows the deviation of machine parameters, so the performance of TMS without any controller.

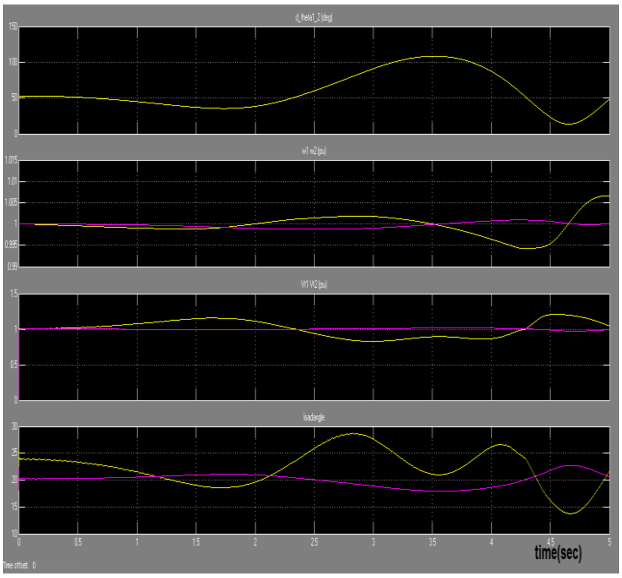

Figure 3.2: Performance parameters of TMS

Fig 3.3 shows the simulation model of HPFC1, its controllers and other modules are also shown in fig 3.3. The model of HPFC1 consists of two series connected converter (VSC), and a passive element (SVC) in shunt. The rating of converters and passive component used in HPFC1 is given in Table 3.4.

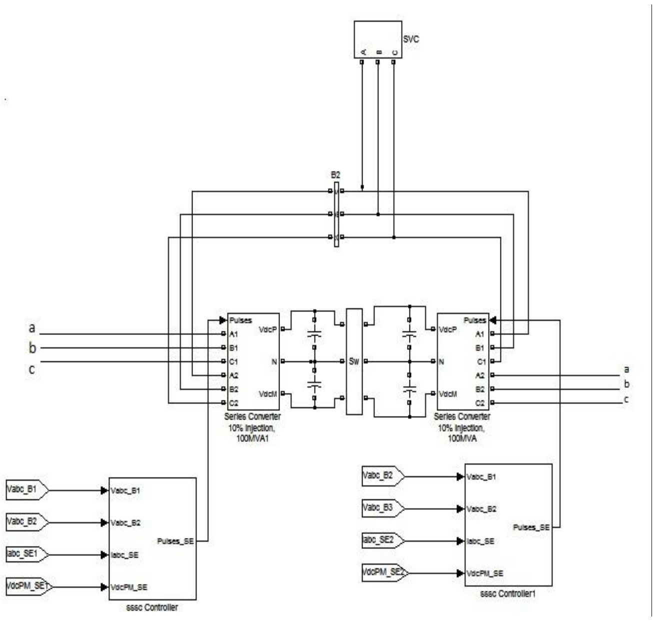

Figure 3.3: Simulation model HPFC1

With the help of power measurement block, the value of power flow through bus B1,B2, and B3 are calculated. Table 3.1 gives the value of power flow.

Table 3.1: Power flow through B1,B2, & B3

	BUS B1	BUS B2	BUS B3
ACTIVE POWER (MW)	877.3	877.3	874.4
REACTIVE POWER (MVAR)	118.3	118.3	4.7

The performance parameters of two machines system with HPFC1 is shown in fig 3.4. Which shows the deviation of machine parameters, so the performance of TMS with HPFC1.

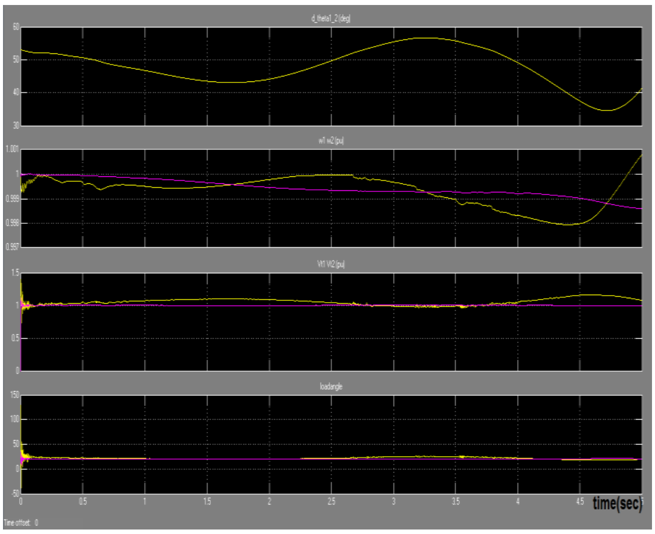

Figure 3.4: Performance parameters of TMS

Fig 3.5 shows the simulation model of TMS with HPFC2, its controllers and other modules are also shown in fig 3.5. The model of HPFC2 consists of two shunt connected converter (VSC), and a passive element (TCSC) in series The rating of converters and passive component used in HPFC2 is given in Table 3.4.

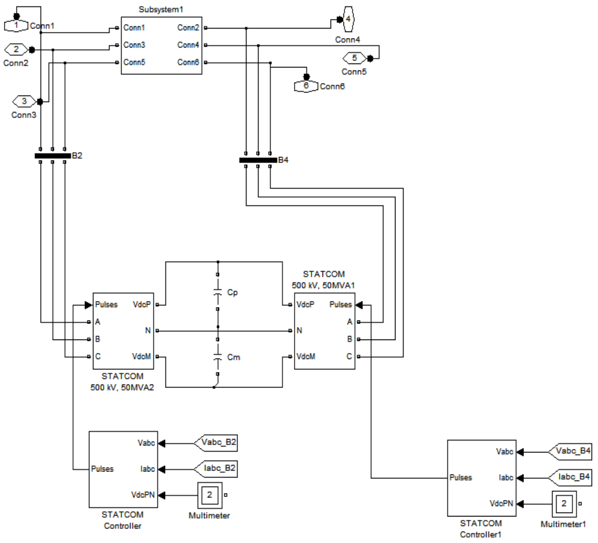

Figure 3.5: Simulation model HPFC2

With the help of power measurement block, the value of power flow through bus B1,B2, B3 and B4 are calculated. Table 3.2 gives the value of power flow

Table 3.2: Power flow through B1,B2, B3, & B4

	BUS B1	BUS B2	BUS B3	BUS B4
ACTIVE POWER (MW)	980.8	243.1	976.4	-239
REACTIVE POWER (MVAR)	-269.3	20.15	-98.14	-35.67

The performance parameters of two machines system with HPFC2 is shown in fig 3.6. Which shows the deviation of machine parameters, so the performance of TMS with HPFC2.

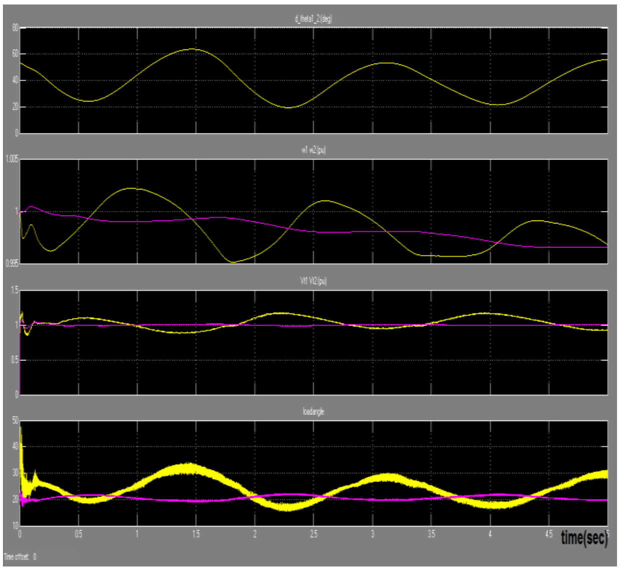

Figure 3.6: Performance parameters of TMS

Fig 3.7 shows the simulation model of TMS with UPFC, its controllers and other modules are also shown in fig 3.7. The model of UPFC consists of two converter (VSC), one is series connected and other one is shunt connected. The rating of converters used in UPFC is given in Table 3.4.

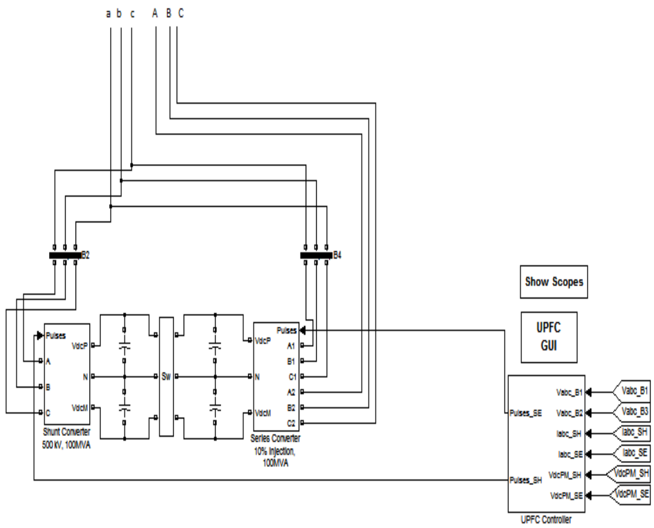

Figure 3.7: Simulation model UPFC

With the help of power measurement block, the value of power flow through bus B1,B2, B3 and B4 are calculated. Table 3.3 gives the value of power flow.

Table 3.3: Power flow through B1,B2, B3 & B4

	BUS B1	BUS B2	BUS B3	BUS B4
ACTIVE POWER (MW)	961.9	68.91	961.2	893
REACTIVE POWER (MVAR)	-138	-31.48	-212.3	-106.6

The performance parameters of two machines system with UPFC is shown in fig 3.8. Which shows the deviation of machine parameters, so the performance of TMS with UPFC.

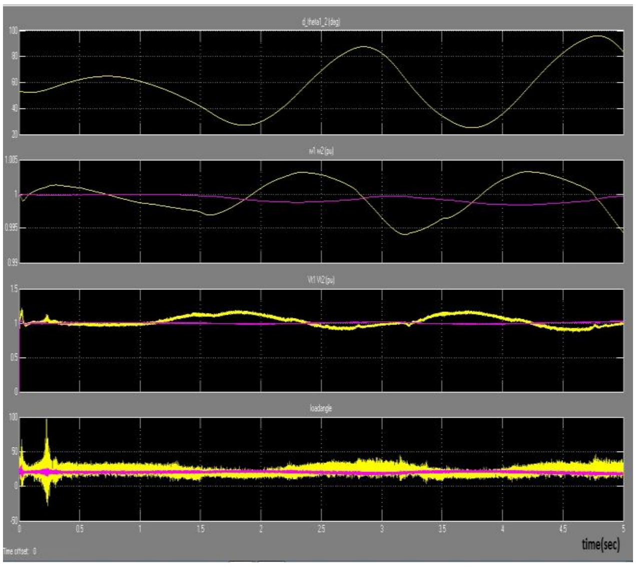

Figure 3.8: Performance parameters of TMS

Table 3.4: Rating of converter and passive compensator

	UPFC	HPFC1	HPFC2
VSC-1	500KV, 100MVA SHUNT CONNECTED	500KV, 50MVA SHUNT CONNECTED	10% INJECTION,50MVA SERIES CONNECTED
VSC-2	10% INJECTION,100MVA SERIES CONNECTED	500KV, 50MVA SHUNT CONNECTED	10% INJECTION,50MVA SERIES CONNECTED
SERIES COMPENSATOR	---	C=21.977e-6F L=0.043H	---
SHUNT COMPENSATOR	---	---	500KV, TCR=109*1 Mvar TSC= 94*3 Mvar
DC LINK CAPCITANCE	C_P=5000e-6F C_M=5000e-6F	C_P=5000e-6F C_M=5000e-6F	C_P=3000e-6F C_M=3000e-6F

IV. CONCLUSION

In this paper, the performance of "Hybrid power flow controller" has been studied. Here two topologies are used for HPFC, labeled as HPFC1 and HPFC2. These topologies of HPFC consist of a passive device with two static converters. The aim of this thesis is to model the HPFC for improving the performance of power system using MATLAB/SIMULINK software and compare it with UPFC.

The "Hybrid power flow controller" (HPFC1 &HPFC2) have been connected to two machine system, consists of a two synchronous machines interconnected through the transformers and transmission line. And the performance of two machine system (power flow control, machine's parameters, and bus voltage) has been analyzed, with and without controllers (HPFC1 &HPFC2). This paper gives all the results, which shows the capability of HPFC to control the power flow through line, and to improve the performance of system. The injected voltage in series with the line is the controlling variable for HPFC, by which HPFC control the power flow. HPFC1 injects a voltage (VC) in series with the line so as the power flow through line is reduced to 877.3 MW from 928.7 MW (natural power flow without controller). And the performance of two machine system is also improved. Similarly HPFC2 injects a voltage (VC) in series with the line so as the power flow through line is increased to 980.8 MW from 928.7 MW (natural power flow without controller).

The UPFC is also modeled and connected in two machine system and its power flow controlling capability is compared with HPFC1 and HPFC2. By comparing the performance results of both the topologies of HPFC and UPFC, and by referring Table 3.4 (Rating of converter and passive compensator) it can be concluded that, "the performance characteristics of HPFC are similar to UPFC without significant reduction in versatility, thus HPFC can be regarded as a performance equivalent and cost effective alternative of UPFC".

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