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Stability Analysis of Single Machine Infinite Bus System with HPFC

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***Abstract*— In recent years, a number of FACTS (Flexible AC Transmission system) controllers have been proposed for better utilisation of existing power transmission facilities. These devices have shown better results when used to improve power system stability. In this paper, Hybrid Power Flow Controller (HPFC) is used to improve the Transient stability of Single Machine Infinite Bus (SMIB) System. All the equations required for this purpose are systematically derived. By setting one control parameter of the HPFC to zero, same equations can also be used to represent a UPFC. A combination of full and continuous controls is used to improve the transient stability limit of a power system in the presence of a HPFC and UPFC and results are compared.**

Keywords—FACTS, perpendicular voltage control, unified power flow controller (UPFC), Hybrid power flow controller (HPFC), full and continuous controls, transient stability

I. INTRODUCTION

The power-transfer capability of long transmission lines is usually limited by large signal stability. On the other hand, the development of effective ways to use transmission systems at their maximum thermal capability has caught much research in recent years. Fast improvement in the field of power electronics has already started to influence the power industry. FACTS offer an alternative solution to transmission expansion by increasing the utilisation of the available facilities towards their thermal limits. With increased power transfer, transient and dynamic stability is more important for safe operation. Fast responding FACTS can be used to improve the stability.

The history of FACTS controllers can be traced back to 1970s when Hingorani presented the idea of high power electronic applications in power system control [1], [2]. Various researches from then onwards were carried out on the applications of high power semiconductors in transmission systems. Based on use of Power electronic devices, FACTS controllers can be classified as:

- Variable impedance type
- Voltage Source Converter(VSC) type

The variable impedance type controllers include:

1. Static Var Compensator (SVC), shunt connected
2. Thyrister controlled series capacitor (TCSC), series connected
3. Thyrister controlled phase shifting transformer (TCPST), Combined shunt and series

These are based on thyrister switched and/or controlled capacitors or reactors. Such controllers have limited performance, limited functionality and large footprint.

The VSC based FACTS controllers include:

1. Static synchronous compensator (STATCOM), shunt connected
2. Static synchronous series compensator (SSSC), series connected
3. Interline power flow controller (IPFC), combined series-series
4. Unified power flow controller (UPFC), combined shunt-series

These controllers have superior performance due to versatile functionality and smaller footprint.

A novel Hybrid power flow controller (HPFC) topology for FACTS was proposed in [3], [4]. It consists a shunt connected controllable source of reactive power, and two series connected voltage source converters, one on each side of the shunt device. The series converters can exchange active power through a common dc circuit as shown in Fig. 1.

The dynamic performance of a power system is improved by dynamically controlling the machine output power and this can be achieved by placing a HPFC at appropriate location. The improvement of transient stability and damping of power system was investigated in [5] for three different modes of operation of the series converter of UPFC: impedance control, perpendicular voltage control and voltage angle control modes. In impedance control mode, the series converter voltage is kept in quadrature with the line current and its magnitude is proportional to the line current. However in perpendicular voltage control mode, series converter voltage is kept in quadrature with the line current but its magnitude is independent of line current. In voltage angle control mode, series converter voltage simply changes the phase angle between input and output voltages. It is clear that from [5] the perpendicular voltage control mode is the simplest and most practical mode of operation of a UPFC. The same technique is used here to control series converters of HPFC. When one of the series converters is kept inactive, the HPFC simply acts as a UPFC.

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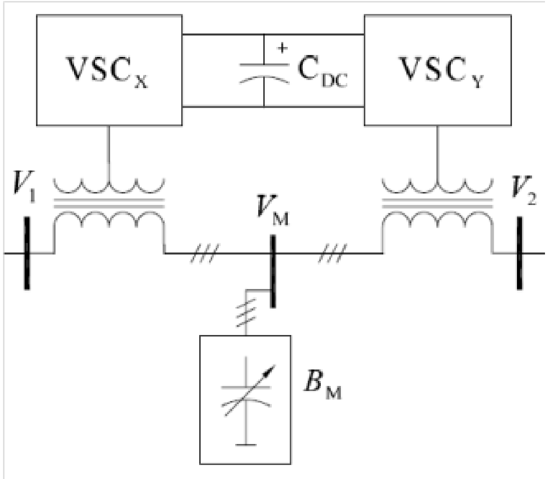

Fig.1. Schematic diagram of HPFC

Continuous control and discontinuous control of FACTS devices are very commonly used to improve the dynamic performance. For small disturbances, continuous control is usually enough to improve damping of power system. For following a large disturbance, a full control is first applied to increase the first swing stability limit and then the control is switched to continuous type to improve damping in subsequent swings. This paper investigates the improvement of the first swing stability limit as well as damping of power system with the help of HPFC. A combination of full and continuous controls is used here.

II. MATHEMATICAL MODEL OF HPFC

Consider a single machine infinite bus (SMIB) system with a HPFC as shown in Fig. 2. The equivalent circuit of the system is shown in Fig. 3.Where the HPFC is represented by two series voltage sources and a shunt current source. In fig. 3. X_1 represents the equivalent reactance between the machine internal bus and intermediate bus m, and X_2 represents the equivalent reactance between bus n and the infinite bus. Here reactance of both series transformers is neglected. The dynamics of the machine, in classical model, can be represented by the following differential equations.

$$\frac{d\delta}{dt} = \omega \qquad \rightarrow (1)$$

$$\frac{d\omega}{dt} = \frac{1}{M}(P_m - P_e - D\omega) \qquad \rightarrow (2)$$

Here δ, ω, M, D, P_m and P_e are the angle, speed, moment of inertia, damping constant, input mechanical power and output electrical power, respectively, of the machine. The output power P_e of the machine can be expressed as

$$P_e = \mathrm{Re}(\mathbf{E}\mathbf{I}_1^*) \qquad \rightarrow (3)$$

Here **E** is the machine internal voltage and $\mathbf{I}_1$ is the current through reactance X_1. By using superposition theorem, $\mathbf{I}_1$ and $\mathbf{I}_2$ can be expressed as

$$\mathbf{I}_1 = \frac{\mathbf{E-V-Vx+Vy-j}X_2\mathbf{I}_s}{\mathrm{j}(X_1+X_2)} \triangleq \mathbf{I}_1\angle\theta_1 \qquad \rightarrow (4)$$

$$\mathbf{I}_2 = \frac{\mathbf{E-V-Vx+Vy+j}X_1\mathbf{I}_s}{\mathrm{j}(X_1+X_2)} \triangleq \mathbf{I}_2\angle\theta_2 \qquad \rightarrow (5)$$

Here **V** is the voltage at the infinite bus and is considered as reference. The voltage at bus *m* can be written as

$$\boldsymbol{V_m} = \mathbf{E} - \mathbf{V_x} - \mathbf{j}\boldsymbol{X_1}\mathbf{I_1} \triangleq \mathbf{V}_m\angle\delta_m \qquad \rightarrow (6)$$

For given machine internal voltage **E** and infinite bus voltage **V**, currents $\mathbf{I}_1$ and $\mathbf{I}_2$ depend on the series voltage sources $\mathbf{V}_x$ and $\mathbf{V}_y$ and shunt current source **I**s of HPFC. When both the series converters of HPFC operates in perpendicular voltage control mode, $\mathbf{V}_x$ is kept in quadrature with $\mathbf{I}_2$ and $\mathbf{V}_y$ is kept in quadrature with $\mathbf{I}_2$ such that no real power exchange in between both the series converters. And shunt current source **I**s is also in quadrature with $\mathbf{V}_m$. When all converters are in capacitance mode, $\mathbf{V}_x$, $\mathbf{V}_y$ and **I**s can be expressed as

$$\boldsymbol{V_x} = \mathbf{V_x}\angle(\boldsymbol{\theta_1} - \boldsymbol{\pi/2}) \triangleq \mathbf{V}_x\angle\alpha \qquad \rightarrow (7)$$

$$\boldsymbol{V_y} = \mathbf{V_y}\angle(\boldsymbol{\theta_2} + \boldsymbol{\pi/2}) \triangleq \mathbf{V}_y\angle\beta \qquad \rightarrow (8)$$

$$\boldsymbol{I_s} = \mathbf{I_s}\angle(\delta_m - \boldsymbol{\pi/2}) \triangleq \mathbf{I}_s\angle\gamma \qquad \rightarrow (9)$$

Here θ_1, θ_2 and δ_m are the angles of $\mathbf{I}_1$, $\mathbf{I}_2$ and $\mathbf{V}_m$ respectively. When all converters are in inductive mode, the values are simply shifted by π with respect to capacitive mode of operation. In this paper, V_x, V_y and I_s are calculated by appropriate control law and angles of these quantities are obtained from the equations

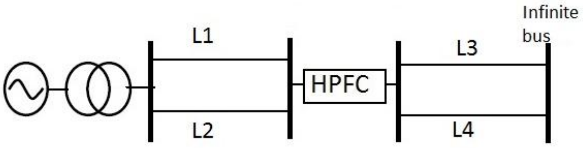

Fig.2. Single line diagram of a SMIB system with HPFC

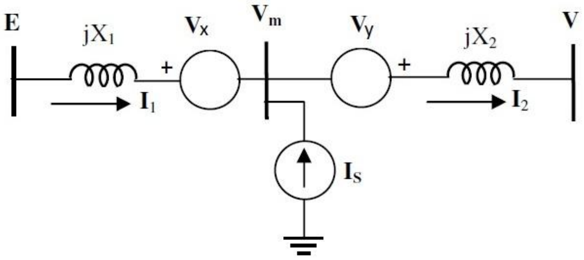

Fig.3. equivalent circuit of a SMIB system with HPFC

$$\alpha = \theta_1 - \pi/2 \qquad \rightarrow (10)$$

$$\beta = \theta_2 + \pi/2 \qquad \rightarrow (11)$$

$$\gamma = \delta_m - \pi/2 \qquad \rightarrow (12)$$

Note that there are no closed form solutions for θ_1, θ_2 and δ_m. However, for given values of V_x , V_y and I_s, values of θ_1, θ_2 and δ_m can be obtained from (4)-(6) by using the following simple iterative scheme[6].

1) Assume initial values of θ_1, θ_2 and δ_m and calculate α, β and γ. using (10)-(12), respectively.
2) Obtain $\mathbf{I}_1$, $\mathbf{I}_2$ and $\mathbf{V}_m$ from (4) - (6), respectively. Determine values of θ_1, θ_2 and δ_m.
3) Update α, β and γ. using (10) - (12), respectively.

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III. CONTROL STRATEGY

The main objective of a controller to improve transient stability, following a large disturbance, is to improve the first swing stability limit. The stability limit can be calculated by equal area criterion for SMIB system. Increasing the swing stability limit involves enlarging the decelerating area as much as possible. It is fully utilized to counterbalance the accelerating area. This can be achieved by operating all three converters in capacitive mode in early part of the post fault period until the machine speed reaches reasonable negative value during the return journey. Afterwards, linear continuous control can be applied to control subsequent swings. Control strategy for this type is given in [6] for UPFC. Keeping this in mind, the same strategy is considered here for controlling HPFC parameters and it is as follows.

During fault condition (when $t < t_c$)

$V_x = 0$;
$V_y = 0$; → (13)
$I_s = 0$;

Post fault condition (when $t < t_c$)

If $\omega > -\xi\omega_m$ *(first swing)*

$V_x = V_x^{max}$;
$V_y = V_y^{max}$; → (14)
$I_s = I_s^{max}$;

Otherwise:

$V_x = k_1\omega; V_x^{min} \leq V_x \leq V_x^{max}$
$V_y = k_2\omega; V_y^{min} \leq V_y \leq V_y^{max}$ → (15)
$I_s = k_3\omega; I_s^{min} \leq I_s \leq I_s^{max}$

Where k_1, k_2 and k_3 are the positive gains and their values depend on the ratings of converters. ω_m is the maximum machine speed and it usually occurs at fault clearing time t_c, and ξ is a small positive constant. V_x^{max} and V_y^{max} and I_s^{max} are the maximum voltage and current ratings series and shunt converters, respectively of HPFC. Here the values of V_x , V_y and I_s are calculated by using the above control strategy.

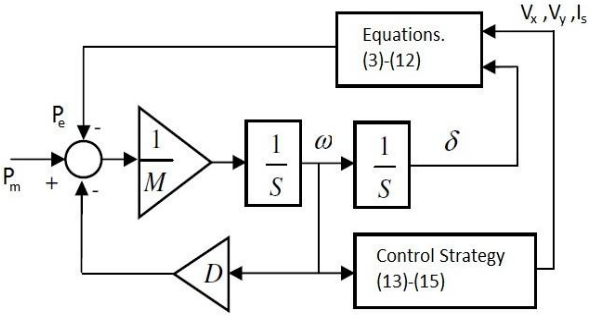

Fig. 4. Simulation block diagram of a SMIB system

IV. SIMULATION RESULTS

The proposed technique, improving the stability limit by using a HPFC is tested on a SMIB system of fig. 3. The system data are taken from [6]. Simulation block diagram of the system with a HPFC is shown in fig.4. By setting the parameter V_x to zero, the same block diagram can also be used to evaluate the system response with UPFC. The critical clearing time (CCT) of fault without device and with UPFC is found from [6] as 101-102 ms and 168-169 ms respectively. It is found that CCT increased to 185-186 ms with HPFC. Here the large disturbance is taken as 3-phase fault and it is considered that this fault occurs in line L3 near bus. Fault is cleared by opening the faulted line at both ends. In this paper the inductive ratings of converters are considered to be the same as the corresponding capacitive ratings, i.e. $\mathbf{V}_x^{min} = -\mathbf{V}_x^{max}$, $\mathbf{V}_y^{min} = -\mathbf{V}_y^{max}$ and $\mathbf{I}_s^{min} = -\mathbf{I}_s^{max}$. The swing curve of the machine, with the HPFC, for a fault clearing time of 160ms is shown in fig.5. The swing curve of the machine obtained by operating HPFC as a UPFC is also shown in fig.5 for comparison purpose. Here the values of V_x, V_y and I_s are considered as 0.2 pu, 0.2 pu and 0.5 pu, respectively. It is clear that from fig. 4, when HPFC operates as UPFC highest peak angle is 121.57^0 during the first swing and stable value of rotor angle is 54.17^0 whereas it operates as HPFC highest peak angle and stable value of rotor angle are 106.88^0 and 54.32^0 respectively. Stable and peak angles for different fault clearing times are tabulated here when operated as both HPFC and UPFC.

TABLE-I:
Stable and peak angles for different fault clearing times with HPFC

Fault clearing time (ms)	Stable rotor angle (deg)	Peak of 1st swing (deg)
100	54.22	69.90
130	54.27	85.69
160	54.32	106.88
180	54.35	130.15

TABLE-II:
Stable and peak angles for different fault clearing times with HPFC operated as UPFC

Fault clearing time (ms)	Stable rotor angle (deg)	Peak of 1st swing (deg)
100	54.16	77.48
130	54.19	94.80
160	54.22	121.57
180	Unstable	--

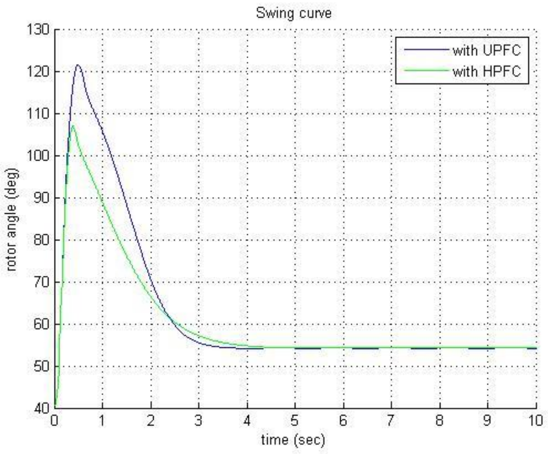

Fig.5. Swing curve of the machine

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V. CONCLUSION

A technique of maximizing the first swing stability limit of a simple power system by dynamically controlling the machine output power with the help of a HPFC is proposed in this paper. All converters of HPFC are first operated at their max ratings in early part of the post fault period to enlarge the decelerating area as much as possible and fully utilizing it in counterbalancing the accelerating area. The control is then switched to linear continuous type to improve damping in subsequent swings.

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