Effect of Time Constant Parameter Uncertainties on Dynamic Performance of interconnected Power Systems with EHVAC/HVDC Transmission Links

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ABSTRACT
This paper presents a comprehensive study on dynamic performance of two-area interconnected power systems when subjected to Time constant parametric uncertainties. Power system model consists of one area with reheat thermal power plants and other area with hydro power plants having identical capacity, the system interconnection considered as namely EHVAC transmission link only, HVDC transmission link with $\Delta P_{dc}$ taken as state variable, HVDC transmission link with $\Delta P_{dc}$ taken as control variable, EHVAC in parallel with HVDC transmission link with $\Delta P_{dc}$ taken as state variable and EHVAC in parallel with HVDC transmission link with $\Delta P_{dc}$ taken as control variable. The dynamic model of incremental power flow through HVDC transmission link is derived based on frequency deviation at rectifier end only. Moreover, the HVDC link is considered to be operating in constant current control mode. To carry out the investigations, optimal AGC regulators are designed using proportional-plus-integral control strategy and implemented on the system under consideration in the wake of 1% step load perturbation in area-1. The effect of $\pm$ 50% variation in system Time constant parameters from their nominal parameter values on system dynamic performance has been studied by investigating the response plots with (i) nominal system Time constant parameters and (ii) $\pm$ 50% variation in system Time constant parameter values. The system responses have been simulated in Mat lab. Responses of $\Delta f_{1}$, $\Delta f_{2}$, $\Delta P_{tie}$, $\Delta P_{dc}$, $I_{ACE1}$ and $I_{ACE2}$ have been plotted for each Time constant parameter variation. The most significant parameters, which influence the system dynamic performance, are identified.

Keywords---- Interconnected power systems; HVDC transmission links; System dynamic Performance; EHVAC//HVDC transmission link; Optimal AGC regulator.

Notations:
- Subscript referring to area (i=1,2)
- $\Delta X_{gi}$ Incremental change in governor valve position of ith area
- $\Delta P_{ci}$ Incremental change in speed changer position of ith area
- $\Delta P_{gi}$ Incremental change in power generation of ith area
- $\Delta P_{di}$ Incremental change in load demand of ith area (p.u. MW/Hz)
- $\Delta F_{i}$ Incremental change in frequency of ith area
- $\Delta P_{tiei}$ Incremental change in tie-line power flow of ith area (MW)
- $\Delta P_{dc}$ Incremental change in DC link power flow of ith area
- $\Delta P_{ri}$ Incremental change in reheat turbine output of ith area
- $H_{i}$ Per unit inertia constant of ith area (sec)
- $D_{i}$ Load frequency constant of ith area (p.u. MW/Hz)
- $R_{i}$ Speed regulation parameter of ith area (Hz/p.u. MW)
- $B_{i}$ Frequency bias constant of ith area (p.u. MW/Hz)
I. INTRODUCTION

Reliable and secure operation of interconnected power systems is a fundamental requirement for the modern societies. The continuous growth in size & complexity of interconnected power systems their operational & control problems have gained paramount significance and their control philosophies have tremendously changed from their earlier classical control concept to the application of modern control theory concepts. Moreover, the advancement in computer era has also revolutionized implementation of control strategies. The operational and control problems mainly aimed at maintaining system variables at their scheduled levels at different instants of system operation satisfying the system constraints. To cope with enormously increasing load demands and subsequently meeting economical, technical and environmental considerations, power engineers are presently motivated to propose generating stations sites remote from the load centers. Moreover, sharing benefits of utilizing variability in generation mixes and load patterns, led to the evolution of interconnected power systems consisting of generating units of widely varying characteristics and sizes. Therefore, this development has necessitated such transmission links which are capable of exchanging the large chunk of electrical power among widely spread power pools effectively and economically fulfilling technical objectives. Till seventies, this requirement was fulfilled by EHVAC transmission lines and later by transmission at rapidly increasing AC voltage levels. However, the power transmission at EHVAC/UHVAC levels and over extra long distances is associated with various operational and control problems. To combat these problems, HVDC transmission systems have emerged on power scenario due to its numerous economical and technical advantages over EHVAC transmission especially for controlled transfer of power between areas operating even at different frequencies, to enhance transient and dynamic stability in the associated AC networks and fast control to limit fault currents. Many HVDC transmission lines are commissioned all over the world and several HVDC projects are envisaged in ensuing years. One of the major applications of HVDC transmission is operating an HVDC link in parallel with an EHVAC link.

India has many options to cope with ever increasing power demands through thermal, nuclear, hydro and non-conventional power generations. However, these options are restricted by associated technical, operational and environmental considerations. Especially, in Indian power scenario, development of electrical power generation through hydro power plants has gained a momentum during last few years due to its inherent feature of being pollution free. Technically the most ideal ratio of hydro and thermal generations should be 40:60[7]. In spite of best efforts, India is far behind to achieve this ratio. Most of the hydroelectric power plants are situated in Southern, North Eastern and Himalayan region in the country. There are possibilities to generate more power from North Eastern and Himalayan regions in future and a
situation may arise for power engineers to have an inter-regional interconnection of hydroelectric power pools and hydrothermal power pools. In a hydro-turbine relatively large inertia of water, used as the source of energy, causes a greater time lag in the response of the change in prime mover torque to a change in gate position. Moreover, there is an initial tendency for the torque to change in a direction opposite to that finally produced. The design and implementation of AGC regulators for power system with hydro turbines offers some technical difficulties due to large time constants associated with hydropower plants [4]. The implementation of optimal AGC regulator, designed with nominal system parameter values, may give rise to the deteriorated system dynamic performance in the wake of system parameter uncertainties. In practical conditions, the system parameters do not remain constant. There may be some variations in the system nominal values due to operating conditions, aging effect, and errors in the measurement or due to assumptions made in simplifying the mathematical model. Thus in presence of system parameters variations, the dynamic performance of the system may get deteriorated and become poor. Hence, for this reason, here, we have taken up a look to study the effect of parameters variations on the system’s dynamic performance and find out most significant parameters.

II. THE TWO AREA POWER SYSTEM MODEL

The two area interconnected hydrothermal power systems consisting of one power system with reheat thermal power plants and other power system with hydro power plants having identical capacity. The following configuration:

(i) EHVAC tie-line is used as a system interconnection.
(ii) HVDC link is used as a system interconnection.
(iii) EHVAC tie-line in parallel with HVDC link is used as a system interconnection.
Let us take an s-area interconnected power system described by a completely controllable and observable linear time-invariant state space representation. The differential equations of the system are can be written as

\[
\dot{X} = A X + B U + \Gamma P_d
\]  

--- (1.1)

\[
Y = C X
\]  

--- (1.2)

Where: \( X \), \( U \), \( \Gamma P_d \) and \( Y \) are the state, control, disturbance and output vectors respectively.

A, B, C and \( \Gamma \) are the matrices of compatible dimensions.

We find the control \( U \), so as to minimize the performance index.
J = \int_{t_0}^{\infty} \left[ \frac{1}{2} X^T Q X + U^T R U \right] dt

--- (1.3)

Where,
Q – a positive semi-definite symmetric state cost weighting matrix.
R – a positive definite symmetric control cost weighting matrix.

In the application of optimal control theory, the term \( \Gamma P_d \) in eqn (1.1) is eliminated by redefining the states and controls in terms of their steady-state values occurring after the disturbance.

Eqn (1.1) can be rewritten as;

\[
\dot{X} = A X + B U \quad X(0) = X_o
--- (1.4)
\]

Where, \( X(0) = X_o \) is the initial condition.

And equation (1.2) will remain same.

With a full state vector feedback control problem, a control law is stated in the form

\[
U^* = -K^* X
--- (1.5)
\]

Hence, in order to design optimal regulator so as to minimize the performance index, we have to solve the Matrix- Riccatti (MR) equation given as:

\[
A^T P + PA - P B R^{-1} B^T P + Q = 0
--- (1.6)
\]

By solving this equation, we get positive definite symmetric matrix \( P \) such that the optimal control law is calculated as

\[
U^* = -R^{-1} B^T P X
--- (1.7)
\]

Hence, the desired optimal feedback gain matrix will be

\[
K^* = R^{-1} B^T P
--- (1.8)
\]

IV. STATE VARIABLE MODEL

(1)(a) System interconnection as EHVAC transmission link only.
(b) System interconnection as HVDC transmission link only, with \( \Delta P_{dc} \) as control variable.
(a4) System interconnection as parallel EHVAC/HVDC transmission link, with \( \Delta P_{dc} \) as state variable.
(a5) System interconnection as parallel EHVAC/HVDC transmission link, with \( \Delta P_{dc} \) as control variable.

(2)State vectors

\[
[X_{a1}] = [\Delta f_1, \Delta P_{g1}, \Delta P_{r1}, \Delta X_{g1}, \Delta f_2, \Delta P_{g2}, \Delta X_{g2}]
\]
\[
[X_{a2}] = [\Delta f_1, \Delta f_2, \Delta X_{g1}, \Delta X_{g2}, \Delta P_{g1}, \Delta P_{g2}, \Delta P_{r1}, \Delta P_{r2}, \Delta P_{dc}, \Delta P_{tie}, \Delta P_{ACE1}, \Delta P_{ACE2}]
\]
\[
[X_{a3}] = [\Delta f_1, \Delta P_{g1}, \Delta P_{r1}, \Delta X_{g1}, \Delta f_2, \Delta P_{g2}, \Delta X_{g2}]
\]
\[
[X_{a4}] = [\Delta f_1, \Delta P_{g1}, \Delta P_{r1}, \Delta X_{g1}, \Delta f_2, \Delta P_{g2}, \Delta X_{g2}, \Delta X_{gh2}, \Delta P_{tie}, \Delta P_{dc}, \Delta P_{ACE1}, \Delta P_{ACE2}]
\]
\[
[X_{a5}] = [\Delta f_1, \Delta P_{g1}, \Delta P_{r1}, \Delta X_{g1}, \Delta f_2, \Delta P_{g2}, \Delta X_{g2}, \Delta X_{gh2}, \Delta P_{tie}, \Delta P_{ACE1}, \Delta P_{ACE2}]
\]

(3)Control vectors

\[
[U_{a1}] = [U_{a2}] = [U_{a4}] = \Delta P_{c1}, \Delta P_{c2}]
\]
\[
[U_{a3}] = [U_{a5}] = \Delta P_{c1}, \Delta P_{c2}, \Delta P_{dc}
\]

(4) Disturbance Vectors

\[
[P_{d-a1}] = [P_{d-a2}] = [P_{d-a3}] = [P_{d-a4}] = [P_{d-a5}] = \Delta P_{d1}, \Delta P_{d2}
\]

V. SYSTEM DATA AND MATRICES

The nominal system parameter values are given in Appendix A. The system matrices are derived based on (i) nominal values of system parameters; (ii) values of system parameters with 50% Reduction; and (iii) values of system parameters with 50% increase. The structure of all system matrices is not reported due to brevity.

SIMULATION RESULTS; The system responses have been simulated in Mat lab programming.
(1) Variations in Tg (governor time constant):

![Graphs showing variations in Tg for different scenarios]

- **EHVAC only**
- **HVDC, ΔPdc State Var.**
- **AC/DC, ΔPdc State Var.**
- **AC/DC, ΔPdc Control Var.**

- **HVDC, ΔPdc Control Var.**

- **EHVAC/DC, ΔPdc State Var.**

- **EHVAC/DC, ΔPdc Control Var.**

- **HVDC, ΔPdc State Var.**

- **EHVAC/DC, ΔPdc State Var.**

- **HVDC, ΔPdc State Var.**

- **EHVAC/DC, ΔPdc Control Var.**

- **HVDC, ΔPdc Control Var.**

- **EHVAC, ΔPdc State Var.**

- **AC/DC, ΔPdc State Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC, ΔPdc Control Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC/DC, ΔPdc Control Var.**

- **AC/DC, ΔPdc State Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC, ΔPdc State Var.**

- **AC/DC, ΔPdc State Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC, ΔPdc Control Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC/DC, ΔPdc State Var.**

- **AC/DC, ΔPdc State Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC, ΔPdc Control Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC/DC, ΔPdc Control Var.**

- **AC/DC, ΔPdc State Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC, ΔPdc State Var.**

- **AC/DC, ΔPdc State Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC, ΔPdc Control Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC/DC, ΔPdc State Var.**

- **AC/DC, ΔPdc State Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC, ΔPdc Control Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC/DC, ΔPdc Control Var.**

- **AC/DC, ΔPdc State Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC, ΔPdc State Var.**

- **AC/DC, ΔPdc State Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC, ΔPdc Control Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC/DC, ΔPdc State Var.**

- **AC/DC, ΔPdc State Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC, ΔPdc Control Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC/DC, ΔPdc Control Var.**

- **AC/DC, ΔPdc State Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC, ΔPdc State Var.**

- **AC/DC, ΔPdc State Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC, ΔPdc Control Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC/DC, ΔPdc State Var.**

- **AC/DC, ΔPdc State Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC, ΔPdc Control Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC/DC, ΔPdc Control Var.**

- **AC/DC, ΔPdc State Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC, ΔPdc State Var.**

- **AC/DC, ΔPdc State Var.**

- **AC/DC, ΔPdc Control Var.**

- **EHVAC, ΔPdc Control Var.**

- **AC/DC, ΔPdc Control Var.**
In case of Tg (above fig ), 50% increment in its nominal value improves system dynamic performance for ∆f1 (EHVAC only, HVDC ∆Pdc as control variable, AC/DC ∆Pdc as state variable), ∆f2 (HVDC ∆Pdc as state variable, AC/DC ∆Pdc as state variable), ∆Ptie (EHVAC/DC ∆Pdc as state variable), IACE1 (HVDC, AC/DC ∆Pdc as control variable) & IACE2 (HVDC, ∆Pdc as state variable), while remaining responses have no considerable effect in the dynamic performance.
In case of Tt (above fig), 50% decrement in its nominal value gives improved system dynamic performance for all cases (i.e. the magnitudes of first peak, oscillatory modes around steady state error & settling time has been reduced marginally).

(3) Variations in T1, T2 and T3 (hydro–governor time constants):

In case of Tt (above fig), 50% decrement in its nominal value gives improved system dynamic performance for all cases (i.e. the magnitudes of first peak, oscillatory modes around steady state error & settling time has been reduced marginally).
In case of T1, T2, T3 (above fig), 50% decrement in its nominal value improves system dynamic performance for $\Delta P_{tie}$ (EHVAC only, AC/DC $\Delta P_{dc}$ as state variable), $\Delta P_{dc}$ (HVDC, $\Delta P_{dc}$ as state variable), IACE2(excluding HVDC, $\Delta P_{dc}$ as control variable). While remaining responses have no considerable effect in the dynamic performance.
(4) Variations in $T_w$ (water inertia time constant):

![Graphs showing variations in $T_w$.]
In case of Tw (above fig ), 50% increment in its nominal value improves system dynamic performance for ∆Ptie (EHVAC only AC/DC ∆Pdc as state variable), ∆Pdc (HVDC ∆Pdc as state variable, AC/DC ∆Pdc as state variable), while remaining responses have no considerable effect in the dynamic performance.
In case of R (above fig), 50% decrement in its value improves slightly the dynamic performance for \( \Delta f_1 \text{(HVDC, } \Delta P_{dc} \text{ as control variable), } \Delta f_2 \text{(HVDC, AC/DC for both } \Delta P_{dc} \text{ as state variable & control variable), } \Delta \text{Ptie, } \Delta P_{dc} \text{ & IACE2. But remaining responses have no considerable effect.}

(6) Variations in B (Speed regulation constant):
In case of B (above fig), 50% increment in its nominal value, the magnitudes of first peak, oscillatory modes around steady state error & settling time has been reduced marginally resulting system dynamic performance improves for all cases. While 50% decrement in its nominal value degrade the system dynamic performance in all aspects of response qualities.

(7) Variations in T12 (EHVAC link synchronizing coefficient):
In case of EHVAC link synchronizing coefficient ($T_{12}$) (above fig), 50% decrement in its nominal value improves the dynamic performance for $\Delta f_1$ (AC/DC $\Delta P_{dc}$ as state variable), $\Delta P_{tie}$ (EHVAC only, EHVAC/DC $\Delta P_{dc}$ as state variable), $IACE_1$ & $IACE_2$ (EHVAC only).

(8) Variations in $K_{dc}$ (HVDC link gain constant):
In case of Kdc (above fig), 50% increment in its nominal value improves the dynamic performance for \( \Delta f_1 \) (HVDC, AC/DC as state variable). But 50% decrement in its nominal value improves the dynamic performance for \( \Delta P_{tie} \), \( \Delta P_{dc} \) (HVDC, EHVAC/DC \( \Delta P_{dc} \) as state variable), whereas 50% increment in its nominal value degrades the system dynamic performance for the same (i.e. \( \Delta P_{tie}, \Delta P_{dc} \) (HVDC, EHVAC/DC \( \Delta P_{dc} \) as state variable)). There is no considerable effect on dynamic performance for \( \Delta f_2 \), IACE1 & IACE2, 50% variations in its nominal value.
(9) Variations in $T_{dc}$ (HVDC link time constant):
There is no considerable effect is observed in the system dynamic performance, In case of 50% variation in Tdc (above fig) for all cases.

(10) Variations in Kr (Reheat coefficient of the turbine):
Above Fig shows that the magnitudes of first peak, oscillatory modes around steady state error & settling time has been reduced marginally for all the system interconnection combinations, in case of 50% increment in nominal value of Kr.
(11) Variations in Tr (Time constant of the reheater):

We observed that responses obtained subjected to the variation in Tr (Fig. P=32 to 34). In case of 50% increment in nominal value, we get improved dynamic performance. But, in case of 50% decrement in nominal value, there is no considerable effect in the dynamic performance.

VI. CONCLUSION

From the investigations carried out for an interconnected hydro-thermal power systems with HVDC link & parallel EHVAC/DC link, the variation in nominal value of system parameters reveal that the system dynamic performance is more sensitive to the variations in Tg, Tr ,B , T12 ,Kdc ,Kr, Tr parameters , while less sensitive to the variations in T1,T2,T3,Tw,R & Tdc parameters. (i) The performance of plotΔf1 improves, by 50% increment in nominal values of parameters Tg, B, Kdc, Kr, Tr and 50% decrement in nominal values of parameters Tt, T12. While there is no considerable affect on ± 50% variation inT1, T2, T3, Tw, R and Tdc.(ii) The performance of plotΔf2 improves, by 50% increment in nominal values of parameters Tg, B, Kr, Tr and 50% decrement in nominal values of parameters Tt, T12, Kdc, Tdc. While there is no considerable affect on ± 50% variation inT1, T2, T3, Tw, and R.(iii) The performance of plot ΔPtie improves, by 50% increment in nominal values of parameters Tg, Tw B, Kr, Tr and 50% decrement in nominal values of parameters Tt, T1, T2, T3, R, T12, and...
Kdc. While there is no considerable affect on ± 50% variation in Tdc.(iv) The performance of plot DC improves, by 50% increment in nominal values of parameters Tg, Tw, B, Kr, Tr and 50% decrement in nominal values of parameters T1, T2, T3, R, T12, and Kdc. While there is no considerable affect on ± 50% variation in Tdc.(v) The performance of plot IACE1 improves, by 50% increment in nominal values of parameters Tg, B, Kr, Tr and 50% decrement in nominal values of parameters T1. While there is no considerable affect on ± 50% variation in T1, T2, T3, Tw, R, T12, Kdc and Tdc.(vi) The performance of plot IACE2 improves, by 50% increment in nominal values of parameters Tg, B, Kr, Tr and 50% decrement in nominal values of parameters T1, T2, T3, R, T12. While there is no considerable affect on ± 50% variation in Tw, Kdc and Tdc.

REFERENCES


Appendix A; Data: For Reheat Thermal Plant ;Pr1 = 2000 MW; H1 = 5 sec; D1 = 0.00833 p.u. MW/Hz; M1=0.167pu MW/Hz; R1 = 2.4 Hz p.u.MW; B1 = 0.425 p.u.MW/Hz; Tg1 = 0.08 sec; Tt1 = 0.3 sec; a12 = -1; ΔPd1 = 0.01; ΔPd2 = 0.02; Kr1 = 0.5; Tr1 = 10 sec; For Hydro plant;Pr2=2000 MW; H2=5 sec; D2=.00833 p.u.MW/Hz; M2=0.167pu MW/Hz; R2=2.4 Hz p.u.MW; B2 = 0.425 p.u.MW/Hz;T1=.0513sec;T2=5 sec;T3=48.7 Sec; Tw=1.0sec; For AC& DC Link; Pmax = 200 MW (10% of Rated Power);2*π*T12=0.545; a = δ1- δ2 = 30°.Kdc = 1.0; Tdc = 0.2.