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DESIGN OF DELAYED-INPUT WIDE AREA POWER SYSTEM STABILIZER USING GAIN SCHDEDULING METHOD

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Abstract: Centralized wide area control design using system-wide data has been suggested to enhance large interconnected power systems dynamic performance. Because of the nature of wide area interconnections, communication delay cannot be ignored in the wide area control. A long time delay may cause a detrimental effect to system stability and degrade system robustness. The general Linear Fractional Transformation (LFT) method to describe the time delay uncertainty can lead to a conservative design. In this paper, a Gain Scheduling (GS) method based on Linear Matrix Inequality (LMI) is proposed to design a dynamic controller to accommodate time delays in supervisory Power System Stabilizer (PSS) design. The new approach achieves better performance than the general LFT method, and the order of the controller remains the same with that of the system plant.

Keywords: Wide Area, Time Delay, Gain Scheduling (GS), Robust Control, Linear Matrix Inequality (LMI), Power System Stabilizer (PSS), Linear Fractional Transformation (LFT).

1. INTRODUCTION

The general configuration of a modern power system is that power sources and consumers are widely dispersed. Generators and loads may be over 1000 miles apart in large systems such as in the Western Electricity Coordination Council (WECC) system. The interconnection of different control areas can improve system security and economy of operation. In recent years, as a consequence of the deregulation of the electric power industry in the United States, the number of bulk power exchanges over long distances between control areas has greatly increased. However the development of generation is much slower than the load increase. According a report from the Electric Power Research Institute [1], generation capacity margin has consistently decreased in the past 20 years. For example, the generation capacity margin in 2000 was only one third of that in 1983. Transmission network expansion in this period also has been stagnant. During the decade from 1988 to 1998, the expansion of transmission capacity was only a half of the increase of electricity demand, while in 1999 to 2009, the ratio was predicted to drop to 17% [1]. All these factors will drive tie lines to operate near their maximum capacity, especially those connected to the heavy load areas such as southern California.

As explained in [4], stressed operating conditions can increase the possibility of inter-area oscillation between different control areas and even breakup of the whole system. The two famous WECC cases in the summers of 1996 and 2000 were both associated with poorly damped inter-area oscillations under conditions of high power transfer on long paths [8]. How to achieve maximum available transfer capability as well as a high level of power quality and security has become a major concern. This concern stimulates the need for a better system control, leading to damping improvement.

There are several control methods employed in power systems with regard to system stability enhancement. A distributed control scheme is usually applied to local power systems, such as Power System Stabilizer (PSS), voltage regulators, and some protective relay systems. Although local optimization is realized to a certain degree during tuning, the controller cannot guarantee performance when the operating point changes and inappropriate coordination among the local controllers occurs. This failure of coordination may cause serious problems such as undamped inter-area oscillations. To solve these problems, centralized controllers using wide area or global signals have been suggested since the 1990s. It is found that if remote signals are applied to the controller design, the system dynamic performance can be enhanced for the inter-area oscillations [2]. The basic mechanism of damping remains as the production of damping torque in synchronous generators through the use of appropriate field excitation. This excitation comes from a supervisory PSS.

In recent years, the fast development of communication technology, low price communication devices, and various communication media make it possible to provide the control center with the real time signals from remote areas. However, the use of centralized controller entails inputs that may arrive after a certain communication delay. In distributed control systems such as protective relay systems, the time delay or *latency* is usually less than 10 ms. Unlike the small time delay in local control, in wide area power systems the time delay can vary from tens to several hundred milliseconds or more. In the Bonneville Power Administration (BPA) system, the latency of fiber optic digital communication is approximated as 38 ms, while latency using modems via microwave is over 80 ms [3]. The delay of a signal feedback in a wide area power system is usually considered to be on the order of 100 ms [2]. If routing delay is included, and if a large number of signals are to be routed, there is a potential of not only experiencing longer delays but also variability in these delays. The large delay can be also caused by waiting for synchronized signals from different areas.

Time delay can make the control system have less damping features. There is a danger of losing synchronism due to time delay. In order to satisfy specifications for wide area control systems, the design of a controller must take into account this delay in order to provide a controller that is robust, not only for the range of operating conditions desired, but also for the *uncertainty in delay* [2]. The impact of time delay on robust controller designs has been ignored in power systems for a long time, but becomes a pertinent topic in recent years with the proposal of wide area power system control.

In this paper, two topics from advanced control theory are applied to the cited problem of supervisory PSS (SPSS) design with uncertain delay. As an illustration of the concept, a four-machine system is used as the test bed for the delayed-input wide-area or SPSS design. Speed deviations from the local generators are measured and send to the controller center. The LMI H_∞ method is used to design the supervisory PSS. It is found that if a controller is designed for delay-free system but applied to the delayed-input system, the closed-loop system may lose stability.

In control systems, time delay can be represented by the Pade approximation [11] and the delay uncertainty can be described by a Linear Fractional Transformation (LFT) [7]. Although the fixed controller designed based on LFT can keep the system stable over the delay uncertainty range, the closed-loop performance is very conservative, resulting in a much larger H_∞ norm for the closed-loop system gain as compared to the delay-free system.

In this paper, a Gain Scheduling (GS) method is proposed to accommodate time delay instead of the general LFT method. GS control is a well-known engineering practice. But the main breakthrough occurred in 1991 with the papers of Packard, Becker and Zhou [10]. The main idea of GS control is to design a parameter-dependent controller that ensures a stable closed-loop system for a given H_∞ bound from *w* (noise) to *z* (controlled signal). The parameters are measured in real time and the desired GS-based controller is dynamic, not fixed. This approach has been applied in various areas such as aircraft control and process control [9]. Unlike a normal robust controller, the GS-based approach provides a dynamic controller for the different variables (in this case, time delay). Simulation shows that system performance with this controller is better than that with the normal robust controller. And the GS approach can be implemented with little extra cost compared to the normal robust controller.

2. Linear Fractional Transformation and Gain Scheduling Method

Linear Fractional Transformation

A time delay uncertainty can be described in a state space realization, which includes a feedback interconnection of a constant matrix and a matrix with dynamic parameters. This realization is called a Linear Fractional Transformation [7]. Let the time delay be given by

$$t_d = a + bd_t \tag{1}$$

where both *a* and *b* are constants and $d_t \in [-1,1]$. The LFT of $1/t_d$ is shown in Fig. 1, where $y_2 = \frac{1}{t_d} u_2$.

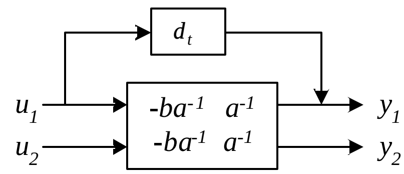

Fig.1 LFT representation of $1/t_d$

The term $1/t_d$ can be represented by a constant matrix and an uncertainty matrix,

$$\frac{1}{t_d} = F_U\left(\begin{bmatrix} -ba^{-1} & a^{-1} \\ -ba^{-1} & a^{-1} \end{bmatrix}, \quad d\right). \tag{2}$$

Suppose the exponential form of time delay $e^{-t_d s}$ in the Laplace domain is replaced by a first-order Pade approximation,

$$e^{-t_d} \approx \frac{-\frac{1}{2}t_d s + 1}{\frac{1}{2}t_d s + 1} \tag{3}$$

with $t_d = 0.175 + 0.125 d_t$ where $d_t \in [-1,1]$. This covers an uncertain time delay from 50 ms to 300 ms. The block diagram of $e^{-t_d s}$ is shown in Fig. 2.

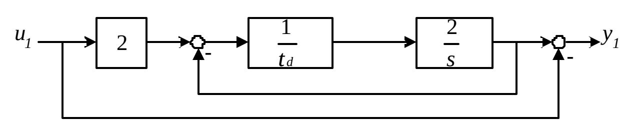

Fig.2 Block diagram of time delay $e^{-t_d s}$

The term $1/t_d$ is then replaced by the upper-loop LFT with an associated matrix M,

$$M = \begin{bmatrix} -0.714 & 8 \\ -0.714 & 8 \end{bmatrix}.$$

By connecting the time delay block with a delay-free system G_m, which includes an uncertainty d_m, the system in Fig. 3 can be constructed and is suitable for the robust controller design. The LMI design based on this structure is conservative for most cases and can be partially improved by m synthesis [10].

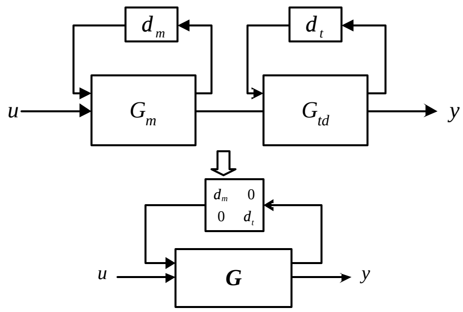

Fig. 3 System connection with the time delay block

Gain Scheduling Method

The main concept of Gain Scheduling control is to design a parameter-dependent controller that ensures closed-loop system stability with a given H_∞ bound from w to z [6]. The parameter is measured in real time and the desired GS-based controller is dynamic instead of fixed. Rather than seeking a single robust Linear Time Invariant (LTI) controller for the entire operating range, GS designs an LTI controller for each operating point and switches controllers smoothly when the operating conditions changes. Conditions for the existence of a parameter-dependent controller that guarantees stability and H_∞ performance for the closed-loop system are given in the form of LMI [9]. These conditions are based on a scaled version of the small-gain theorem, with a symmetric scaling matrix. This GS design method is not only for linear parameter-dependent systems, but also is applicable to time-varying or nonlinear systems whose linearized dynamics are well approximated by parameter-dependent models [6].

Provided that the parameter values are measured in real time, it is desirable to use controllers that incorporate such measurements to adjust to the current operating conditions. Such controllers are scheduled by parameter measurements. This control strategy typically achieves higher performance in the case of large variations in operating conditions [6].

If a system plant is expressed as

$$\begin{aligned} \dot{x} &= A(q)x + B_1(q)w + B_2u \\ z &= C_1(q)x + D_{11}(q)w + D_{12}u \\ y &= C_2x + D_{21}w + D_{22}u \end{aligned} \qquad (4)$$

The objective of H_∞ controller design using GS is to seek a parameter-dependent controller in the form

$$\begin{aligned} \dot{x}_k &= A_k(q)x + B_k(q)u \\ y_k &= C_k(q)x + D_k(q)u \end{aligned} . \qquad (5)$$

Given the convex decomposition

$$q = \sum_{i=1}^{n} a_i q_i ,$$

the values of $A_k(q)$, $B_k(q)$, $C_k(q)$ and $D_k(q)$ can be derived as

$$\begin{pmatrix} A_k(q) & B_k(q) \\ C_k(q) & D_k(q) \end{pmatrix} = \sum_{i=1}^{n} a_i \begin{pmatrix} A_{kq_i} & B_{kq_i} \\ C_{kq_i} & D_{kq_i} \end{pmatrix} \qquad (6)$$

In other words, the controller state-space at the operating point q is obtained by convex interpolation of the LTI vertex controllers

$$\begin{pmatrix} A_{kq_i} & B_{kq_i} \\ C_{kq_i} & D_{kq_i} \end{pmatrix}.$$

This yields a smooth scheduling of the controller matrices by the parameter measurements q. This synthesis problem can be reduced to the following LMI problem: find two symmetric matrices R and S such that

$$\begin{pmatrix} N_{12} & 0 \\ 0 & I \end{pmatrix}^T \begin{pmatrix} A_{q_i}R + RA_{q_i}^T & RC_{q_i}^T & B_{1q_i} \\ C_{q_i}R & -gI & D_{11q_i} \\ B_{1q_i}^T & D_{11q_i}^T & -gI \end{pmatrix} \begin{pmatrix} N_{12} & 0 \\ 0 & I \end{pmatrix} < 0 \quad i = 1, \cdots, N$$

$$\begin{pmatrix} N_{21} & 0 \\ 0 & I \end{pmatrix}^T \begin{pmatrix} A_{q_i}^T S + SA_{p_i} & SB_{1qi} & C_{1q_i}^T \\ B_{q_i}R & -gI & D_{11q_i} \\ B_{1q_i}^T & D_{11q_i}^T & -gI \end{pmatrix} \begin{pmatrix} N_{12} & 0 \\ 0 & I \end{pmatrix} < 0 \quad i = 1, \cdots, N \qquad (7)$$

$$\begin{pmatrix} R & I \\ I & S \end{pmatrix} \geq 0$$

and N_{12} and N_{21} are bases of the null spaces of (B_2^T, D_{12}^T) and (C_2, D_{21}) respectively [6]. And the controller format can be derived from R, S and g .

The parameter q may be an index of operating conditions or a signal interested to the designers. Many implementations of the GS control use a MATLAB LMI toolbox which provides a set of commands to realize the GS-based H_∞ controller design.

This method can be applied to the controller design for a system with time delay uncertainty. Consider a delayed-input system without the controller in Fig.4.

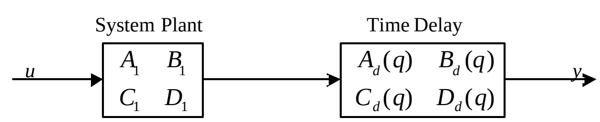

Fig. 4 Delayed-input system

If the time delay block is approximated by the first order Pade Approximation in (3), the state expression for the delay is then derived as

$$\begin{aligned} \dot{x} &= -\frac{2}{t_d}x + \frac{4}{t_d}u \\ y &= x - u \end{aligned} \qquad (8)$$

Substitute q for $1/t_d$, then

$$\begin{aligned} A_d(q) &= -2q \quad B_d(q) = 4q \\ C_d(q) &= 1 \quad\; D_d(q) = -1 \end{aligned} \qquad (9)$$

After connecting the system plant model and the time delay block, the delayed-input system plant can be depicted as in Fig. 5.

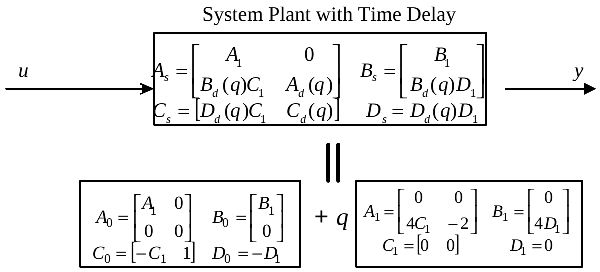

Fig. 5 System connection and the parameter-dependent form

The lower part of Fig. 5 is the standard parameter-dependent model and GS-based H_∞ controller design can be implemented upon this model.

3. RESULTS OF CASE STUDIES

A 4-generator system in Fig. 6 is used as a test system to illustrate the robust control design cited above. This system has been used by many studies on PSSs. It is assumed that no local PSSs are installed. Each generator measures the local speed deviation and sends it to the SPSS, which then sends back a signal to adjust the exaction system of each generator. The modeling of nominal system plant is similar to that in [5], but with four inputs and four outputs. The SPSS acts with the synchronized signals from each area.

Before designing the SPSS, five operating conditions resulting in different tie line (Bus5-Bus6) flows from 0 to 400 MW are tested for the open loop system. It is found that the greater the power flowing through the tie line, the lesser the smallest damping ratio for the inter-area modes. Unstable inter-area modes occur when the tie line flow is over 400 MW. The 400 MW tie line flow case is chosen as the nominal operating point in this study. The objective of the SPSS is to provide system stability and good damping over the tie line flow changing from 0 to 400 MW. Fig.7 describes the connection between the SPSS controller and the system plant.

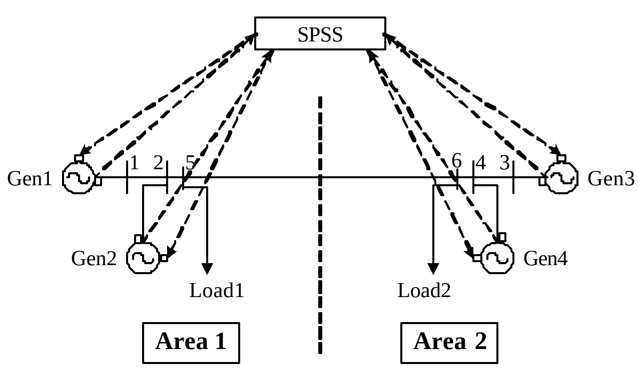

Fig. 6 A four-machine system with SPSS

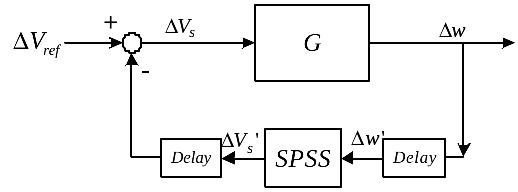

Fig.7 SPSS controller

The state space expression of the SPSS controller is

$$\dot{X}_k = A_k X_k + B_k U_k$$
$$Y_k = C_k X_k + D_k U_k \tag{10}$$

where

$$U_k = [\Delta w'] \qquad Y_k = [\Delta V_s'] \;.$$

$\Delta w'$ = delayed speed deviations

$\Delta V_s'$ = SPSS signals before delay

Three robust control designs for SPSS are compared: a normal H_∞ controller design ignoring time delay (denoted as NHND), a normal H_∞ controller design considering time delay uncertainty in LFT (denoted as NHDU), and a GS-based H_∞ controller design (GSHD). For illustration purposes, a step response test is used. A step input is added to Generator 1 reference signal (ΔV_{ref1}) and the speed deviation of Generator 3 is monitored. The value of time delay in the following figures is the sum of signal upstream and downstream propagation time and other process time involved, which can be measured or estimated. Since the SPSS controller acts with synchronized signals from each area, the time delay in each communication channel is assumed to be the same.

The normal H_∞ controller design ignoring time delay (NHND) is tested to evaluate the controller robustness over the operating range. The H_∞ norm of the closed loop system is within 0.012 to 0.0138 when the tie line flow changes from 0 to 400 MW. The step responses in time domain (Fig. 8) also demonstrate that the closed loop system is stable under disturbances. The generator speed and frequency are kept nearly constant. But the NHND controller can only provide damped response up to 50 ms time delay. The large speed deviation due to a longer time delay in Fig. 9 can lead to separation of the interconnected system into two isolated systems.

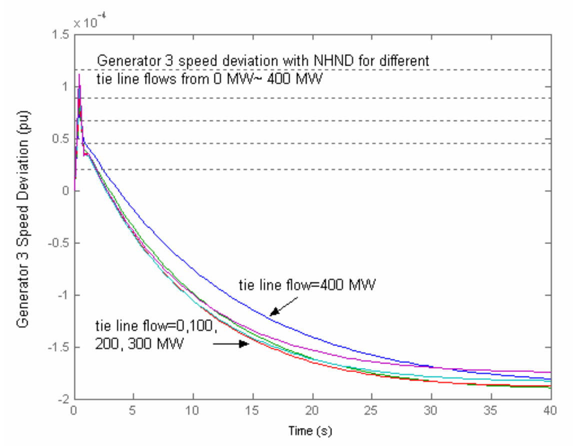

Fig. 8 Step response of Generator 3 speed deviation with NHDU for different tie line flows

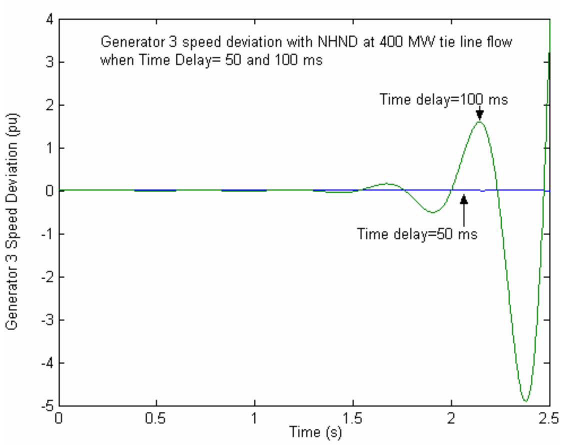

Fig. 9 Step response of Generator 3 speed deviation with NHND for different time delays

At this point, the normal H_∞ controller considering time delay uncertainty (NHDU) is designed using LMI. The time delay uncertainty within the range of 50 to 300 ms is described by an LFT. It is found that NHDU can keep the system stable even with a large time delay. However the H_∞ norm of the closed loop system is about 0.47 for different time delays, which is much larger than the NHND design. The step responses in time domain (Fig. 10) also illustrate large final values of the speed deviation, about –0.025 pu. This corresponds to 0.15 Hz lower than the nominal frequency for a 60 Hz system. This is an unacceptable operating regime.

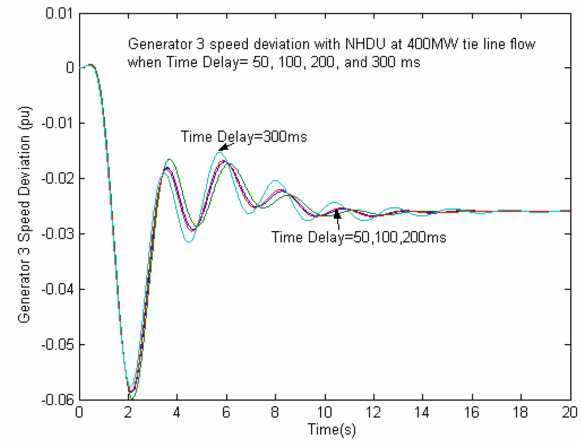

Fig. 10 Step response of Generator 3 speed deviation with NHDU for different time delays

Unlike the NHDU fixed controller, the GSHD approach automatically switches the controller when time delay changes. Compared to the normal design, a real-time measurement or estimation of the time delay is needed for switching controllers. The delay can be derived by comparing the signal time tag and the current time or other methods. The H_∞ norm of the closed loop system is kept at about 0.04 for different time delays. The frequency deviation is only 0.03 Hz lower than the nominal frequency according to the results in Fig. 11. Moreover, the order of the GSHD controller remains the same with that of the system plant.

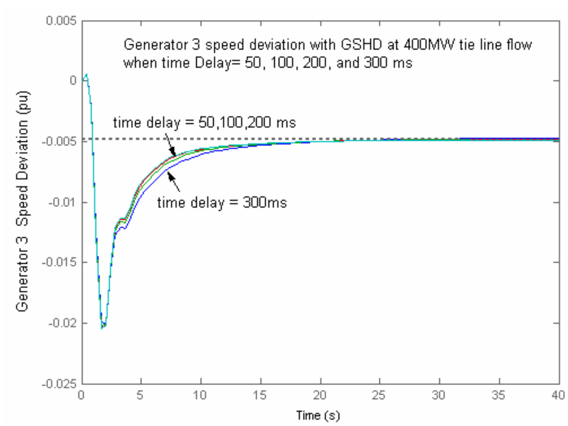

Fig. 11 Step response of Generator 3 speed deviation with GSHD for different time delays

Fig. 12 compares the step response of Generator 3 speed deviation with the three controllers when there is a 50 ms time delay. The GSHD design can achieve a better performance than the NHDU design.

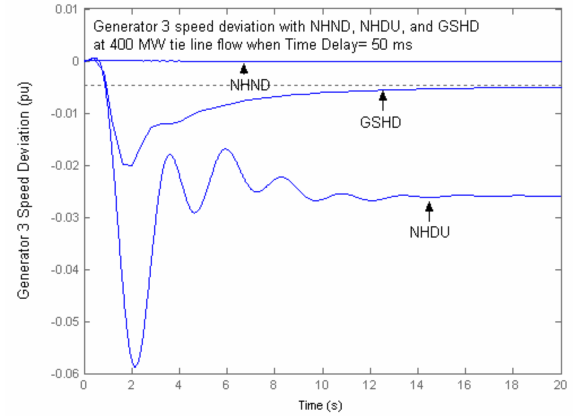

Fig. 12 Comparisons of the system performance with three controllers for a 50 ms time delay

4. CONCLUSIONS

In an interconnected wide area power system, the centralized power system stabilizer utilizes signals which arrive after a certain time delay. This time delay is not only large but also uncertain compared to that experienced in a local system. If the supervisory PSS is designed for a delay-free system but applied to the delayed-input system, the closed-loop system response may be unacceptable. Using the general LFT method to describe the time delay uncertainty may lead to a conservative system performance, which is not capable to keep the system frequency in an acceptable range. A Gain Scheduling method based on LMI is proposed to accommodate different time delays in this paper. This approach produces a dynamic controller and automatically changes the exact format when time delay varies. Simulation shows that this controller not only keeps the system stable under different time delays, but also results in good system performance such as the H_∞ norm of the closed-loop system. Moreover the controller order remains the same with that of the system plant. And the GS approach can be implemented with little extra cost compared to the normal robust controller.

5. ACKNOWLEDGEMENT

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