Understanding a Type of Forced Oscillation Caused by Steam-turbine Governors

Yanhui Xu, *Member, IEEE*, Zheng Gu, Kai Sun, *Senior Member, IEEE*, and Xin Xu

***Abstract*—This paper studies the mechanism of a type of forced power system oscillation induced by imperfect nonlinearity compensation with a steam-turbine governing system. The nonlinear valve control characteristic of a steam turbine is usually compensated by its inverse characteristic performed by its governor for an overall linear characteristic of the governing system. In reality, a governing system may remain nonlinear due to imperfect compensation, which can result in a limit cycle forcing the generator and even an extensive neighboring area of the power grid to oscillate at a low frequency. A compensation imperfection index is proposed to evaluate the residual nonlinearity and discover how a limit cycle can occur and cause forced oscillation of a steam-turbine generator. Time-domain simulation on a real forced oscillation event caused by a steam-turbine governor validates the finding of the paper and supports the fact that opening the governor control loop of the oscillation-source generator can effectively eliminate this type of forced oscillation.**

***Index Terms*—Oscillations, phasor measurement unit (PMU), steam-turbine governor, valve flow characteristics**

I. Introduction

GOVERNORS are essential components of primary frequency regulation in a power system. However, many oscillation events indicate that a governor system, if not configured properly, can induce sustained oscillation of a power transmission system. A malfunctioning steam extractor valve of a steam turbine is considered to be the oscillation source of the Western American oscillation event on November 29, 2005, [1]. A hydropower plant operating in its rough zone caused the 0.37Hz forced oscillation of the Western Interconnection in 2013 [2]. Changes in the control mode of a governor system in Shandong power grid of China caused sustained power oscillations in June 2012, as reported by [3]. Another sustained oscillation event in China Southern Power Grid (CSPG) occurred in 2013, which was also mainly caused by a steam-turbine governor. This paper studies the mechanism of a type of forced power system oscillation caused by a steam-turbine governor, which is found to be driven by a limit cycle due to imperfect compensation of the nonlinear valve characteristics with the turbine. Then an imperfection index is proposed to evaluate the residual nonlinearity and discover how a limit cycle can occur and cause forced oscillation.

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II. Mechanism of Governor-induced Oscillation

To understand the mechanism of this type of oscillation, consider the small-signal model of a single machine infinite bus system: [1]

$$\frac{2H}{\omega_0}\Delta\ddot{\delta}+\frac{K_D}{\omega_0}\Delta\dot{\delta}+K_S\Delta\delta=\Delta T_m \tag{1}$$

$$\Delta\dot{\delta}=\Delta\omega \tag{2}$$

where K_S and K_D are synchronous torque and damping torque coefficients, $2H$ is the inertia constant, and ω_0 is the synchronous angular speed. Controlled by its governor, the mechanical power can be expressed by

$$\Delta T_m=-\Delta\omega G_{gov}(s)f(\Delta\omega)+A_m cos\omega_m t \tag{3}$$

Here, $G_{gov}(s)$ is the transfer function of the linear component of the governor. $f(\Delta\omega)$ represents the governor's nonlinear component depending on the size of speed deviation $\Delta\omega$. For example, if governor deadband is considered, $f(\Delta\omega)=0$ when $|\Delta\omega|$ is within a threshold. $A_m cos\omega_m t$ represents an external periodic disturbance, which may be introduced by other unmodeled effects with the steam-turbine power plant.

A nonlinear equation can express the system as follows.

$$\begin{bmatrix}\Delta\dot{\delta}\\ \Delta\dot{\omega}\end{bmatrix}=\begin{bmatrix}0 & 1\\ -\frac{\omega_0 K_s}{2H} & -\frac{K_D}{2H}\left(1+\frac{\omega_0}{K_D}G_{gov}(s)f(\Delta\omega)\right)\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta\omega\end{bmatrix} \tag{4}$$

How to express the nonlinearity is very important to understand the mechanism of oscillation caused by governor systems. Here we use a polynomial to show the nonlinearity of governor systems since it is convenient to obtain parameters of a polynomial from the measured data.

$$f(\Delta\omega)=\sum_{i=0}^{n}A_i\,(\Delta\omega)^i \tag{5}$$

where n and A_i are the order and coefficient of the polynomial, .

Fig.1 illustrates the power oscillations in time domain and the phase space for three typical cases:

Case (a): A_m=0, i.e. no external periodic disturbance, and $f(\Delta\omega)\equiv1$, i.e. ignoring nonlinearity. The mechanical power is decomposed as $\Delta T_m=-K_{Sm}\Delta\delta-(K_{Dm}/\omega_0)\Delta\omega$. Here K_{Sm} and K_{Dm} are the mechanical synchronous torque and damping torque coefficients and they can be derived from the decomposition of the $G_{gov}(s)$. Let $2H=1$, $k=\omega_0(K_S+K_{Sm})=3$ and $b=K_D+K_{Dm}$ take three different values: 0.1, 0,

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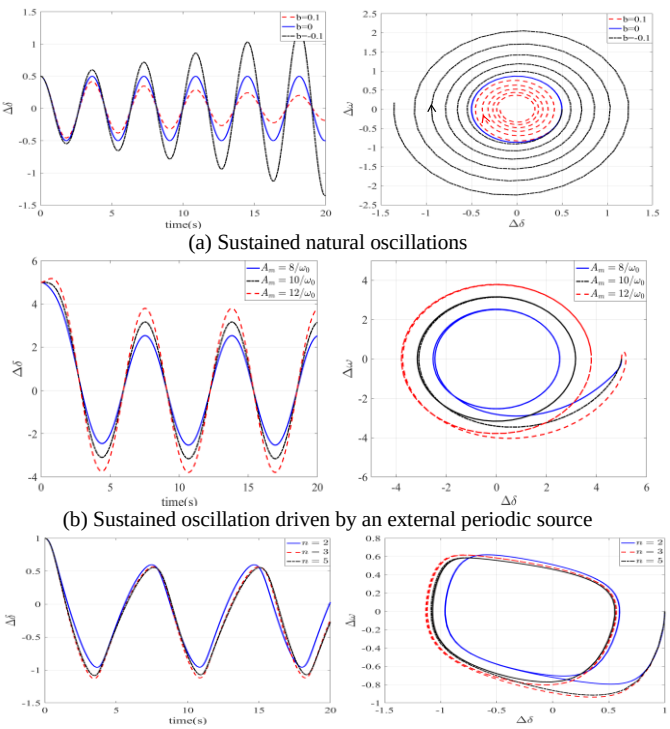
and -0.1.

Case (b): A_m>0, i.e. with an external periodic disturbance, and the system has sufficient damping. Let $2H = 1$, k=$\omega_0(K_S + K_{Sm})$ =2, $b = K_D + K_{Dm} = 3$, A_m=8/ω_0, 10/ω_0, and 12/ω_0.

Case (c): A_m=0, and consider the nonlinearity of $f(\Delta\omega)$. Let $2H = 1$, $\omega_0 K_S$=1, $K_D = -1.5$, the order of the polynomial n=2, 3, and 5.

These three cases illustrate different causes of three types of sustained oscillations. The first type is caused by insufficient or negative damping of a natural mode of the small-signal model, and the other two types are usually considered forced oscillation since the sources of oscillation are not inherent with the small-signal model of the system: the second type is caused by an external periodic disturbance and the third is driven by a limit cycle arising from a nonlinear component of the governing system as modeled by the polynomial function $f(\Delta\omega)$ in (3).



(a) Sustained natural oscillations

(b) Sustained oscillation driven by an external periodic source

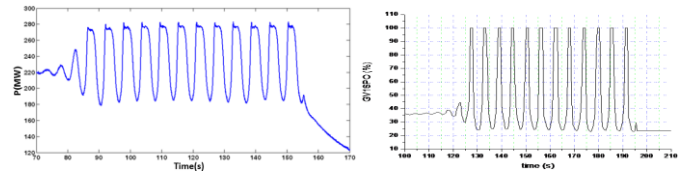
(c) Sustained oscillation driven by nonlinear limit cycles

Fig. 1. Illustration of three types of sustained oscillations

This paper focuses on understanding the third type, i.e. limit-cycle driven oscillation. The rest of the paper utilizes a true oscillation event to show that $f(\Delta\omega)$ can exist due to the governor's imperfect compensation of nonlinearity with the steam turbine, and it can be identified from field measurements.

III. A Sustained Oscillation Event from CSPG

This event involved a coal-fired power plant in CSPG with two turbine generators having a rated power of 330MW. On May 8, 2013, the two units reconnected to the gird after maintenance. Units 1 and 2 respectively generated 220MW and 230MW. When unit 1 began to perform a switching operation of the valve control mode, a sustained oscillation occurred and caused its active power to swing in the range of 186 to 279 MW. The oscillation lasted for 77 seconds. Fig. 2 shows the active power captured by a PMU, and the valve fluctuation recorded by the digital control system (DCS) of the power plant. It should be noted that the time of the DCS lagged behind that of the PMU by about 40s.



(a) Active power (b) The control valve

Fig.2. Oscillations of unit 1 recorded by PMU and DCS

The power plant operator monitored the oscillations and reduced the unit's real power through manual control of the valves. Then, the oscillation quickly subsided. In the manual control mode, the valves are directly controlled by the operator, not automatically. This was a typical event of forced oscillation induced by a steam-turbine governor.

A. System model

Since the sustained oscillation only occurred between the power plant and the main grid, an equivalent model on the power plant connected to the power grid is considered as shown in Fig.3 and system parameters are given in Table I.

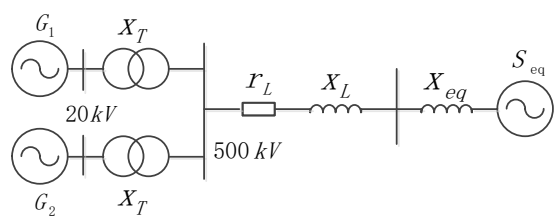


Fig.3. The equivalent system model

TABLE I
PARAMETERS OF THE EQUIVALENT SYSTEM

Symbol	Quantity	Value
x_T	transformer reactance	0.14 pu
r_L	transmission line resistance	0.003 pu
x_L	transmission line reactance	0.06 pu
x_{eq}	system equivalent reactance	0.007 pu

The steam-turbine and governor model considering valve control mode switching (between "1" and "2") is shown in Fig.4. P_{ref} is the reference active power, μ_c is control signal of the valve, μ_{cT} is control signal after the inverse characteristic, μ_T is valve position, p_T is the steam pressure, D_T is the steam flow, and P_m is the mechanical power. Since the turbine valve component from μ_T to D_T under both operation modes is nonlinear, its inverse characteristics are added between μ_c and μ_{cT} respectively for two modes to compensate nonlinearity for an overall, approximately linear governing system. The quantities and typical values represented by the symbols in the turbine and governor are shown in Table II.

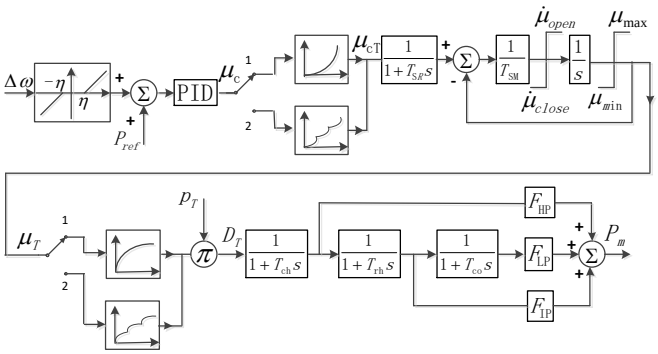


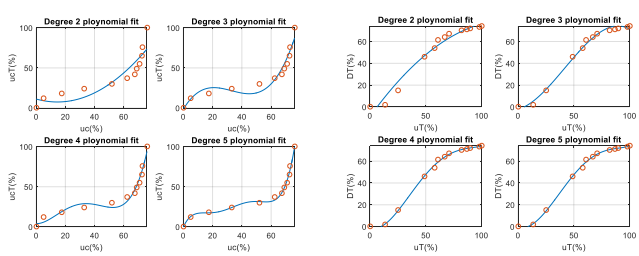
Fig.4. The steam-turbine and governor model

There are two kinds of valve control mode, i.e., mode-1, unified valve control and mode-2, sequential valve control. In mode-1, the four control valves (CVs) opens or closes simultaneously, and the total valve flow satisfies a nonlinear characteristic. In mode-2, two of the four CVs are simultaneously opened and closed, and the other two sequentially open when the first two approach full opening. Thus, the total valve flow characteristic in mode-2 is described by a three-stage nonlinear curve. Mode-1 has the turbine heated more evenly than mode-2 but at a higher throttling loss, so it is mainly for the start-up phase of the unit, while mode-2 is for regular operations at a lower throttling loss.

TABLE II
TYPICAL PARAMETER VALUES OF STEAM TURBINE GOVERNOR

Symbol	Quantity	Value
T_{ch}	inlet chamber time constant	0.28 seconds
T_{rh}	reheater time constant	7 seconds
T_{co}	crossover time constant	0.4 seconds
F_{HP}	power coefficient of HP cylinder	0.3
F_{IP}	power coefficient of IP cylinder	0.4
F_{LP}	power coefficient of LP cylinder	0.3
η	deadband limiting value	0.067%
T_{SR}	speed relay time constant	0.1seconds
T_{SM}	servo motor time constant	0.1seconds
μ_{max}	valve position upper limit	1.0
μ_{min}	valve position lower limit	0.0
$\dot{\mu}_{open}$	valve open rate limit	0.1pu per second
$\dot{\mu}_{close}$	valve open rate limit	0.1pu per second

B. *Fitting of valve flow characteristics*



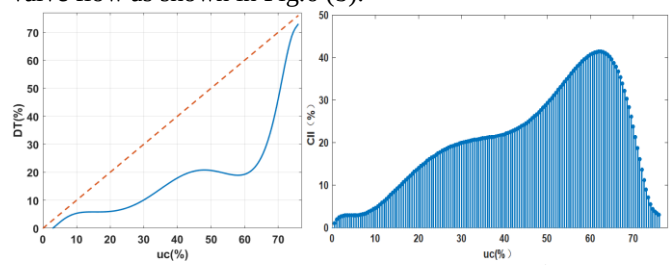
(a) The inverse characteristics (b) The valve flow characteristics

Fig.5. Fitting of the valve flow and its inverse characteristics

The nonlinear valve flow characteristic and its inverse are estimated by 2nd to 5th polynomial fitting as shown in Fig. 5, where circles represent measurements, and solid lines represent the fitting. The 5th order polynomial has the best fit, by which the curve on the valve control signal versus steam flow is shown by the solid line in Fig.6 (a). Ideally, it should be a straight line, as shown by the dashed line. We propose the following compensation imperfection index (CII):

$$CII = \frac{\mu_c - D_T}{D_N} \times 100\% \tag{6}$$

where D_N is the rated steam flow. $CII \equiv 0$ for ideal compensation. For this governing system, the $CII>0$ and changes with the valve flow as shown in Fig.6 (b).



(a) Governing system nonlinearity (b) Compensation imperfection index

Fig.6. The nonlinearity of governor and the compensation imperfection index

There is a strong nonlinearity between the control signal and the valve flow since the inverse characteristic does not entirely offset the valve flow characteristic. Especially for the operating point of unit 1, the active power of 220MW corresponds to a control signal of 67% in terms of 330MW rated capacity.

C. *Mechanism of the sustained oscillation*

The CSPG oscillation mainly occurred at 0.17Hz between a power plant and the grid and did not propagate much to a wide area. It is much slower than the power plant local mode. The CSPG oscillation disappeared immediately when the governing system switched to manual control, which confirmed that the oscillation was not driven by an external periodic source. Thus, the remaining nonlinearity of the imperfect compensation by the governor and the resulting limit cycle are identified as the root cause of the oscillation. Through polynomial fitting, the overall nonlinear characteristic of the governing system can be identified as shown in Fig.7, where a limit-cycle is presented.

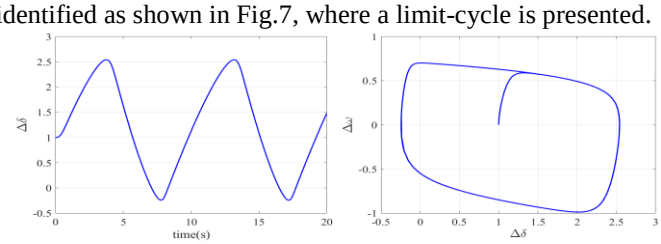
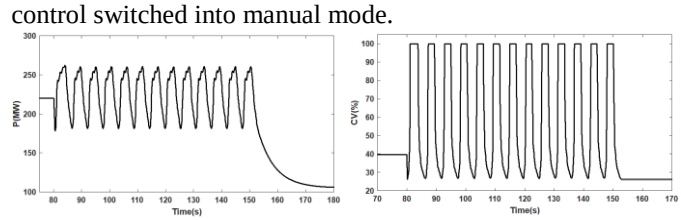


Fig.7. The mechanism of the CSPG oscillation

D. *Verification by time-domain simulation*

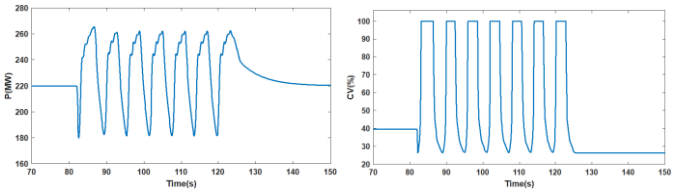
The system model in Fig. 3 is simulated using PSCAD/EMTDC, where the valve flow characteristic and its inverse are set the same as the polynomial fitting results. At the 80s, unit 1 switched from the unified valve control mode into a sequential valve control mode. Then, the active power and valve position began to fluctuate with a frequency of 0.17Hz, as shown in Fig.8. The oscillation subsides until the valve control switched into manual mode.



(a) Active power (b) Governor valve position

Fig.8. Simulation of the CSPG oscillation

Changing the operating point of the unit by manual control is only a temporary measure in emergency. Carefully setting the inverse characteristics of the valve flow to reduce the remaining nonlinearity of the governor system is an effective way to prevent such oscillations. The CII is a very useful indicator to guide the setting of the inverse characteristics of the valve flow. In the following simulation, instead of switching the valve to manual control, the inverse characteristic of the valve flow is switched to the fully compensated characteristic at 120s with CII is equal to 0.



(a) Active power (b) Governor valve position

Fig.9. Simulation of two different sets of governor parameters

From Fig.9, we can see that the oscillation disappears rapidly when switched to the ideal inverse characteristic and the limit cycle is not observed.

IV. Conclusion

This paper discovers the mechanism of a type of forced oscillation driven by a limit cycle caused by imperfect compensation of nonlinearity in steam-turbine generators. A compensation imperfection index is proposed to evaluate how such a limit cycle can arise. The findings are verified on a real oscillation event. When a steam-turbine generator reconnects to the gird after maintenance, it is important to ensure the governor to provide sufficient compensation of the nonlinearity valve flow characteristic with the turbine. As an emergency measure to eliminate this type of oscillation, a measure is to switch the governor to manual control, which is also verified in this paper. In a large power system, a forced oscillation can excite some natural oscillations. The closer its source frequency is to the frequency of a natural mode, the more significantly the natural mode may oscillate if the mode has insufficient damping under the current condition [4]. How this type of forced oscillation interacts with natural oscillation will be our future work.

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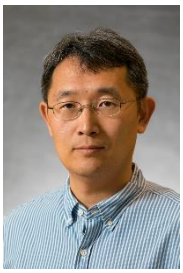

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