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# Forced Power Oscillation Caused by Prime Mover Power Disturbance

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## ABSTRACT

A lot of power and electrical researchers have paid much attention to the forced oscillation mechanism of power system low frequency oscillations. It points out that when the frequencies of cyclic load variations and interconnected network fluctuations coincide with the natural frequency of an oscillation mode, the power system will undergo a resonance. In this paper, the forced power oscillation owing to prime mover power disturbance in a thermal power plant is studied in view of a new strong modal resonance mechanism. As it is known that the Proportional-Integral (PI) controller in the speed-governor has a great effect on system eigenvalues, its parameters may be changed so that the system can pass close to strong resonance. Then, the optimization model is built to seek the speed-governor's parameters in the resonance point and the Particle Swarm Optimization (PSO) algorithm is used here. Finally, the proposed idea is tested on a single machine infinite bus (SMIB) system and the parameters at resonance can be obtained. Under this case, the results of eigenvalue analysis and time-domain simulation suggest that when the parameters of the speed-governor are varied, the system indeed passes close to a strong modal and the mechanical power oscillation occurs. Therefore, it is proved that the prime mover power disturbance can be the source of power system forced power oscillations, and further the assumption of sinusoidal mechanical power disturbance is reasonable during the analysis of forced power oscillation.

## 1. INTRODUCTION

Several mechanisms have been suggested to better understanding low frequency oscillations and the negative damping mechanism (Demello, 1969) has been widely accepted by power and electrical engineers. Moreover, the forced power oscillation mechanism is another profound theoretical achievement, which is based on resonance theory. It indicates that the forced power oscillation may be caused by a sustained cyclic small disturbance in power system. If the frequency of the sustained cyclic small disturbance is close to an inherent oscillation frequency, the resonance could be induced, leading to forced power oscillation with high amplitude. However, a new strong modal resonance mechanism for forced power oscillations is proposed in Dobson

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(2001).

According to the existing studies, the cyclic load variations (Van Ness, 1966), (Rao, 1988), (Rostamkolai, 1994), and the interconnected network fluctuations (Magdy, 1990) are found to be the main sources of the forced power oscillation. In Vournas (1991), the origin of forced low frequency oscillations introduced in power systems by low-speed diesel generators has been intensively investigated.

Nevertheless, there exist two issues on the forced power oscillations. Firstly, most of the power plants are thermal or hydraulic in modern power systems. It is evident that the forced power oscillations caused by prime mover power disturbance are much more serious than those caused by cyclic loads and network fluctuations. However, the possibility of oscillations caused by the prime mover power disturbance in these power plants has not been carefully investigated and assessed. Secondly, it is commonly assumed that the mechanical power disturbance of a generator is sinusoidal in the analysis of low frequency oscillation of resonance mechanism (Xin, 2008). Its rationality should be studied and the condition with a sinusoidal and periodic mechanical power disturbance is needed to search.

In this paper, the forced power oscillation caused by prime mover power disturbance is studied on a SMIB system and the sinusoidal mechanical power disturbance of a generator can be proved.

## 2. PROBLEM FORMULATION

The strong resonance mechanism of forced power oscillation is illustrated mathematically in Dobson (2001). It elaborates that when power system parameters change, two different damped oscillatory modes may move close and interact so as to cause strong resonance. Additionally, a 3-bus and a 9-bus power system are given as examples and they can pass near strong resonance by adjusting active power of the generators. While, this paper will expound that when the parameters of prime mover model are changed, the system can come close to strong resonance.

Firstly，the simplified prime mover models are built according to the function and composition of prime mover. The whole models contain three parts: the Turbine Control Model (TCM), the Electro-Hydraulic Control Model (EHC), and the Steam Turbine Model (STM). Fig. 1 shows the relationship among these parts, generator model (GEN) and network.

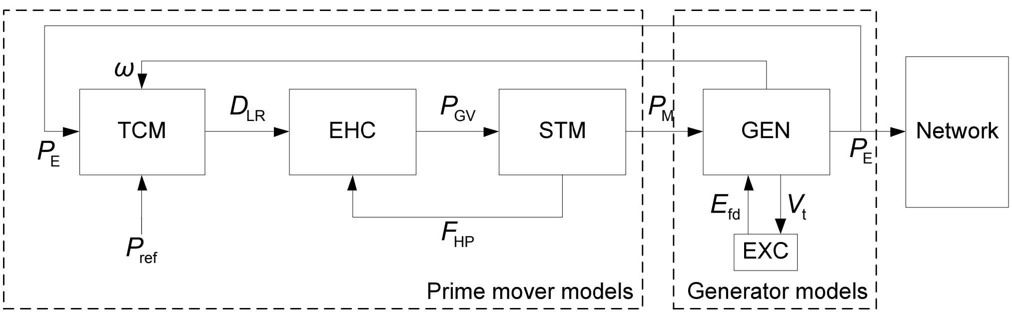


Fig. 1 Schematic diagram of a thermal power unit

Here, $P_E$ is the active power of generator output, and its reference value is $P_{ref}$. The real-time generator speed is $\omega$. $D_{LR}$ is the turbine load reference signal and the high pressure steam flow rate is $F_{HP}$. The governing valve lift is $P_{GV}$ and $P_M$ is the mechanical power. Excitation system model (EXC) regulates field voltage $E_{fd}$ in accordance with terminal voltage $V_t$. The detailed EHC model (IEEE Committee, 1973) is shown as Fig. 2.

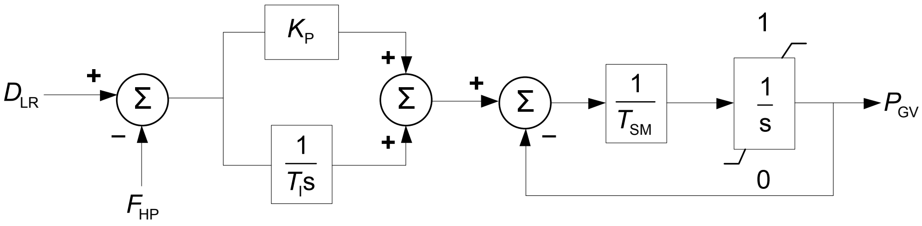


Fig. 2 EHC model

$K_P$ and $T_I$ are the proportional gain and the time constant of the PI controller, and $T_{SM}$ is the servomotor time constant. Through analyzing and computing, the two parameters $K_P$ and $T_I$ have a significant impact on system eigenvalues. So they are excepted to be varied to cause strong resonance.

Secondly，the values of $K_P$ and $T_I$ in strong resonance are sought. As it is known that there are $n-1$ kinds of electromechanical modes in a system with $n$ generators, and there is at least one control mode related to the generator with prime mover. So one electromechanical mode related to the $x$th generator is chosen and its corresponding conjugate eigenvalues are assume as $\lambda_1=\sigma_1+j\omega_1$ and $\lambda_2=\sigma_1-j\omega_1$. The control mode of prime mover in $x$th generator is selected and its corresponding conjugate eigenvalues are assume as $\lambda_3=\sigma_2+j\omega_2$ and $\lambda_4=\sigma_2-j\omega_2$. The two modes may come close and interplay by changing $K_P$ and $T_I$ of $x$th generator.

In order to pass close to strong resonance, it is needed to let the frequencies and damping ratios of the two modes as equal as possible. That is, the distance between the two modes is made as close as possible in the complex plane. The optimization model can be built as following.

$$\begin{aligned} &\text{Obj. min } |\lambda_1-\lambda_3| \\ &\text{s.t. } K_P^{\min} \le K_P \le K_P^{\max} \\ &\qquad T_I^{\min} \le T_I \le T_I^{\max} \\ &\qquad \text{real}(\lambda_j) \le 0, j=1,2,\ldots,m \end{aligned} \tag{1}$$

Here, the objective function is to make the distance between $\lambda_1$ and $\lambda_3$ as small as possible by adjusting $K_P$ and $T_I$. $K_P^{\min}$ and $K_P^{\max}$ are the lower and upper limit of $K_P$. $T_I^{\min}$ and $T_I^{\max}$ are the lower and upper limit of $T_I$. $\lambda_j$ is the $j$th eigenvalue of the system, and there are $m$ eigenvalues in the system. Except the zero eigenvalue, the real parts of other eigenvalues should be less than zero so that the system can remain stable.

According to Eq. (1), it is important to distinguish the electromechanical mode and the control mode from all the oscillation modes. The control mode can be identified by using eigenvalue sensitivities of $K_P$ and $T_I$, and the sum of their amplitudes in the control mode is larger than others. On the other hand, the electromechanical mode is recognized through participation factor. The participation factor $p_{ki}$ of the $k$th state variable in the $i$th mode is defined as:

$$p_{ki} = u_{ki} v_{ki} \tag{2}$$

Here, $u_{ki}$ and $v_{ki}$ are the $k$th entry of the right eigenvector and the left eigenvector in the $i$th mode. The participation factor $p_{ki}$ is a measure of the relative participation of the $k$th state variable in the $i$th mode. All the participation factors in the $i$th mode constitute the participation vector $\boldsymbol{p}_i$. If the element with the maximum amplitude in the participation vector $\boldsymbol{p}_i$ is related to generator speed, the $i$th mode is regarded as an electromechanical mode. In this way, the desired electromechanical mode can be found.

In this paper, the PSO algorithm (Zhang, 2008) will be used to obtain the values of $K_P$ and $T_I$ in order to meet the condition of strong resonance. Then, the SMIB system will be simulated to prove the above idea.

## 3. THE SIMULATION IN SMIB SYSTEM

The SMIB system is shown in Fig. 3 and the simulation will be conducted.

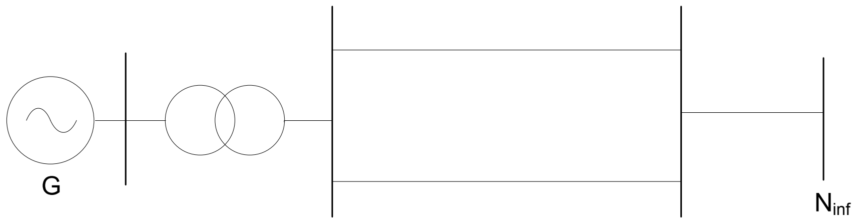


Fig. 3 Single machine infinite bus system

Here, the generator G uses the 5th order model, and there is a self-shunt static excitation system model in it. Its prime mover models include TCM, EHC and STM. For eigenvalue analysis and transient simulation, the infinite bus $N_{inf}$ is connected with a generator of the 2th order model. Under a normal operation, the active power and reactive power of generator G are 300MW and 145Mvar.

After the PSO calculation, the values of $K_P$ and $T_I$ in strong resonance are achieved. In order to contrast, another two groups of $K_P$ and $T_I$ are chosen according to their ranges, as shown in Tab. 1.

Tab. 1 Three groups of $K_P$ and $T_I$

| Case | $K_P$ | $T_I$ |
|---|---|---|
| 1 | 1.8000 | 0.0600 |
| 2 | 1.3969 | 0.0493 |
| 3 | 1.3181 | 0.0467 |

Here, case1, case2 and case3 respectively represent the values of $K_P$ and $T_I$ before, as and after the strong resonance, and the values of case2 is the result of PSO.

The parameters of case1~case3 are plugged into the EHC model, and the system eigenvalues are computed. After ignoring the zero eigenvalue and real eigenvalues, part eigenvalues are shown in Tab. 2.

Tab. 2 Part eigenvalues of the system

| Case | Eigenvalues | Frequency (Hz) | Damping Ratio (%) | Electromechanical Relative Coefficient |
|---|---|---|---|---|
| 1 | −0.4782±j6.1082 | 0.9722 | 7.81 | 5.1322 |
| | −0.7058±j4.7592 | 0.7574 | 14.67 | 0.07464 |
| 2 | −0.3637±j5.5890 | 0.8881 | 7.47 | 3.3767 |
| | −0.4182±j5.5799 | 0.8895 | 6.49 | 0.1566 |
| 3 | 0.06781±j5.6710 | 0.9026 | −1.20 | 2.5653 |
| | −0.7341±j5.6346 | 0.8968 | 12.92 | 0.2288 |

At case1, the electromechanical mode is −0.4782±j6.1082 and the control mode is −0.7058±j4.7592. Their frequencies differ greatly and their damping ratios are both large. At case3, the electromechanical mode is 0.06781±j5.6710 and its damping ratio is less than zero. The control mode is −0.7341±j5.6346 and its damping ratio is larger than 10%. At case2, the electromechanical mode is −0.3637±j5.5890 and the control mode is −0.4182±j5.5799. Their frequencies and damping ratios are very close, which meets the requirement of strong modal resonance.

From Tab. 1, there is a small difference between the $K_P$ and $T_I$ values of case2 and case3. However, when the parameters vary from case2 to case3, the eigenvalues move obviously. This is because the eigenvalues are very sensitive to parameter variations at a strong resonance, and a small change of some parameters can result in an obvious variation of the eigenvalues. Furthermore, it is found that the right eigenvectors of the two modes are nearly aligned at strong resonance, which implies the pattern of oscillation of the two modes is nearly similar.

Next, the transient stability analysis is conducted with a 2% step of reference voltage of the exciter at $t$=1~6s in three cases. Then, the response mechanical power ($P_M$) of generator G is analyzed after the small disturbance disappearing from 7s to 30s, as shown in Fig.4.

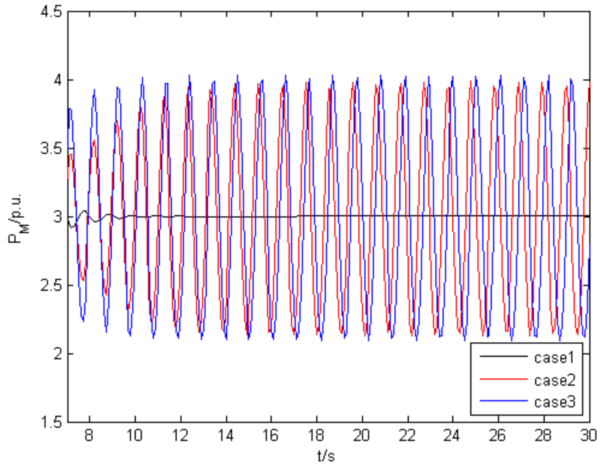


Fig. 4 The response curve of mechanical power

At case1, $P_M$ quickly returns to the normal value after some small oscillations. However, as case2 and case3, $P_M$ firstly stays increasing oscillation and then keeps sustained oscillation after 12s. The former is due to the strong modal resonance, and the latter results from the negative damping. From the $P_M$ response curve of case2, it's realized that when the parameters of EHC are varied, the SMIB system indeed passes close to strong resonance and remain forced power oscillations. Since the system has no load or tie line, it draws a conclusion that the source of the forced power oscillation is the prime mover power disturbance. Additionally, the amplitudes of the forced power oscillation (case2) and the negative damping oscillation (case3) are almost equal. So the influence of the forced power oscillation is also great.

To analyze the $P_M$ curve of case2 in Fig. 4, the Prony theory is used here. Without some DC components, the main modes are shown in Tab. 4.

Tab. 4 Results of Prony analysis

| Mode | Amplitude | Damping | Frequency (Hz) | Damping Ratio (%) |
|---|---|---|---|---|
| 1 | 0.5287 | −0.6377 | 0.9590 | 10.5235 |
| 2 | 0.4633 | −0.000035 | 0.8903 | 0.0006 |
| 3 | 0.3629 | −1.7607 | 0.8368 | 31.7555 |
| 4 | 0.0940 | −1.8085 | 0.5272 | 47.9220 |
| 5 | 0.0777 | −0.6872 | 0.5752 | 18.6797 |
| 6 | 0.0639 | −1.2225 | 0.6534 | 28.5368 |
| 7 | 0.0560 | −1.8474 | 0.9193 | 30.4620 |
| 8 | 0.0286 | 0.0001 | 0.5795 | −0.0029 |
| 9 | 0.0078 | −1.0425 | 0.2874 | 49.9928 |
| 10 | 0.0009 | 0.0005 | 0.3799 | −0.0228 |
| 11 | 0.0001 | −0.0497 | 1.1750 | 0.6732 |

Here, the $P_M$ curve includes eleven types of oscillation modes and the amplitudes of mode1~mode3 are bigger. However, the damping ratios of mode1 and mode3 are larger so they will rapidly decay. The damping ratio of mode2 is very small and its amplitude is nearly unchanged. Therefore, mode2 is the main one. Compared with the two modes of case2 in Tab. 2, their frequencies are about equal.

Hence, at case2, the $P_{M}$ increment after 12s can be approximately expressed as $\Delta P_{M}(t)=\Delta P$◌̇◌̇$\cdot\sin(\omega t)$. Apparently, the stabilized $P_{M}$ curve is varying as a sine wave. It is reasonable that the mechanical power disturbance of a generator is regarded as sinusoidal in the analysis of forced power oscillation.

To avoid modal resonance, it is effective to change power flow. Suppose that the $K_{P}$ and $T_{I}$ of EHC are still equal to the values of case2, but the active power of generator G is added to 400MW. Under this condition, the system eigenvalues are shown in Tab. 5.

Tab. 5 The complex eigenvalues of the system

| Eigenvalues | Frequency (Hz) | Damping Ratio (%) | Electromechanical Relative Coefficient |
|---|---|---|---|
| −0.1821±j5.1815 | 0.8247 | 3.51 | 0.07088 |
| −0.5068±j6.5556 | 1.0434 | 7.71 | 5.9263 |

Here, the frequencies and the damping of the electromechanical mode and the control mode differ greatly. The system cannot come close to strong resonance. Therefore, changing power flow can avoid the strong resonance.

## 4. CONCLUSIONS

This paper mainly analyzes the forced power oscillations caused by the prime mover power disturbance in view of the strong modal resonance. According to the optimization model and the PSO algorithm, the values of $K_{P}$ and $T_{I}$ at strong resonance can be found. The SMIB system is used to test this idea. When $K_{P}$=1.3969 and $T_{I}$=0.0493, the system can indeed pass close to a strong modal resonance and lead to mechanical power oscillations. The results of eigenvalue analysis and time domain simulation suggest that the prime mover power disturbance can be the source of power system forced power oscillations, and prove that the assumption of sinusoidal mechanical power disturbances is reasonable in the analysis of forced power oscillation. Additionally, strong resonance can be prevented by changing the active power of the generator.

## ACKNOWLEDGEMENT

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