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# A CONTRIBUTION IN SOLVING THE PROBLEM OF ELECTRO-MECHANICAL RESONANCE IN THE LARGE-SCALE POWER SYSTEMS PART, I.

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ABSTRACT:

This paper presents a contribution in solving a relatively new power system dynamic problem, namely Electro-Mechanical resonance (EMR). Determination of the Electro-mechanical resonance frequency mainly aims at trying to avoid the occurance of the severe failures caused by the resonance problem.

There are many parameters affecting the value of the EMR frequency such as the electric load, mechanical inertia, and the parameters of automatic voltage and speed regulators.

In this paper, a new approach for measuring the EMR frequency is introduced. The approach is based upon using the most effective parameters from the above mentioned ones in order to separate the resonant frequency of the electromechanical oscillation and the frequency of the limit cycle in such a way that the EMR problem will never occur.

A multimachine system example is introduced in order to clarify the proposed approach and to explain the effect of the mechanical inertia and the Automatic Voltage Regulator on the EMR problem.

## I. Introduction:

Large scale power system stability considerations have been recognized as an essential part of the system planning for a long time. The very extensive interconnection of power systems with greater dependence on firm power flow over ties magnifies the undesirable consequences of instability. Moreover, this may complicates the analytical processes through which reasonable system behaviour is guaranteed.

The mentioned consequences of instability in an interconnected system were dramatized by the North-east power Failure [1,2,3] of 1965 in USA. The logic reason for such a Failure is the electro-mecanical resonance (EMR) i.e. the resonant frequency of the electromechanical oscilafion ($\omega\rho$) is equal to the frequency of the limit cycle ($\omega\ell$). The limit cycle might occur since there are nonlinearties in the power system such as the saturation nonlinearity. Changes in design and operation since then assures that such failure will not happen again. One of the proposed design techniques is to separate the large scale system into subsystems. That is because system separation means that the system inertia is decreased. Consequently, the resonent frequency $\omega\rho$ is increased and the resonance will never occur. The question now is what is affecting $\omega_\rho$ and $\omega_\ell$?

It is the purpose of this paper to answer that question i.e. to find the most important factors affecting the two frequencies $\omega\rho$ and $\omega\ell$. Then, to develop new techniques so as to overcome the occurance of the electromechanical resonance (EMR).

The power system used in this paper is the one that was derived by Yasin and Bishr [4]. The advantages of using such a model are: the stiffness of the model differential equation is overcome, and it has a reduced dimension and precise form. What is meant by precise form is that the results obtained from the analysis using such a model is much closer to the real system ones.

We begin in section II by developing a new aproach for determining the resonant frequency of the electromechanical oscillation ($\omega\rho$) for the multimachine electric power system. Also, the frequency of the limit cycle ($\omega\ell$) will be determined. In section III, the effect of Automatic voltage regulator (AVR)parameters on both frequencies $\omega_\rho$ and $\omega_\ell$ are introduced. Section IV, illustrates the effects of the mechanical inertia on the resonant frequency $\omega\rho$ and the frequency of the limit cycle frequency $\omega\ell$.

## II. A New Approach for Determining The Resonant Frequency of Electromechanical Oscillation:

The classical method for determining the electromechanical Oscillation (EMO) frequency was carried out by using the 24 n th order differential equation model, where n is the number of machines. Then, the eigenvalues of the 24 n x 24 n coefficient matrix is calculated using the digital computer.

This approach is too difficult especially for systems involve large number of machines. Since the computer facility is limitted, that approach is too expensive to use and takes much time to solve such a problem. Even if the solution is accessible it may not be accurate.

Therefore, it becomes necessary to develop a new approach involving a simpler model by which the EMO frequency can easily be calculated even for large number of machines. Su simple model is developed in [5] and it can be rewritten as follows:

For the n-machine system shown in Fig. 1, the dynamical equation for each machine is,

$$\begin{bmatrix} A_{11} & A_{12} \end{bmatrix} \begin{bmatrix} L_g \\ L_b \end{bmatrix} = 0 \qquad (1)$$

where,

$$A_{11} = \begin{bmatrix} 1 & 0 & \Psi_{q_o} & r+SX_d(s) & X_q(s) & 0 & S\,g(s) \\ 0 & 1 & -\Psi_{d_o} & -X_d(s) & r+SX_q(s) & 0 & -g(s) \\ 1 & 0 & 1/s[V_{q_o} - SX_T i_{q_o}] & -X_T S & -X_T & 0 & i_{q_o} g(s) \\ 0 & 1 & 1/s[V_{d_o} + SX_T i_{d_o}] & X_T & -X_T S & 0 & 0 \\ 0 & 0 & \omega_o J S & -\Psi_{q_o} + i_{q_o} X_d(s) & \Psi_{d_o} - i_{d_o} X_q(s) & 0 & 0 \\ \cos\delta_{g_o} & \sin\delta_{g_o} & 0 & 0 & 0 & V_o & 0 \\ V_{d_o} G_{VT}(s)/V_o & V_{q_o} G_{VT}(s)/V_o & 0 & i_{d_o} G_{IT}(s)/i_o & i_{q_o} G_{IT}(s)/i_o & G_{\delta T}(s) & -1 \end{bmatrix} \qquad (2)$$

$[7\text{x}7]$

$$, A_{12}\ [7\times2] = \begin{bmatrix} \sin\delta_o & -\cos\delta_o & 0 & 0 & 0 & 0 & 0 \\ V_{q_o} & -V_{d_o} & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

$$, L_g\ [7\times1] = [\Delta v_{d_g} \quad \Delta v_{q_g} \quad \Delta\omega \quad \Delta i_d \quad \Delta i_q \quad \Delta\delta_g \quad \Delta V_f\ ]^T$$

$$, L_b[2\times1] = [\ \Delta V \quad \Delta\delta\ ]^T$$

| | |
|---|---|
| $\delta_{d_o}$ , $\delta_{q_o}$ | = Operating point values of the stator fluxes in d and q axes respectively, |
| $r$ | = Stator resistance, |
| $X_d(s), X_q(s), g(s)$ | = Operational reactances and conductance of the stator respectively, |
| $\delta_{g_o}$ , $\delta_o$ | = Power angles at the operating point of the machine terminal and the busbar respectively, |
| $V_{d_o}, V_{q_o}, i_{d_o}, i_{q_o}$ | = Operating point values of the voltages and currents in d and q axes respectively, |
| $\omega_o$ | = Synchronous frequency, |
| $J$ | = Constant of inertia, |
| $X_T$ | = The transformer equivalent reactance, |
| $G_{VT}(s), G_{IT}(s), G_{\delta T}(s)$ | = Overall transfer function of voltage, current and frequency channels of AVR. |

The two equations of active and reactive power balance are added to the system in order to have a square coefficient matrix of dimension 9.

Note that for n-machine system, the model dimension becomes 9n. To reduce this very large scale model, one can use only the model of the desired machine, and take the effect of the other n-1 machines into consideration [5]. Therefore, the n-machine model is written in the following form:

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & B_{22} \end{bmatrix} \times \begin{bmatrix} \Delta L_g \\ \Delta L_p \end{bmatrix} = 0 \qquad (6)$$

Where, $B_{22}$ is of order 2 and represents the effect of n-1 machines into the machine under consideration.

It is clear from the above mentioned model that the multi-machine electric power system model can be reduced to be only of order 9 independent of the number of machines.

The nine state variables of that reduced model can easily be used to determine the resonant frequency of the EMO. This can be done by plotting magnitudes of the normalized state variables of equation (4) against the frequency $\omega$, and find the frequency at which such magnitudes are maximum.

Now, to determine the frequency of the limit cycle, the classical technique can easily be used [6]. The overall linear transfer function of the system is predetermined. Then the Nyquist plot along with $-1/N$ curve of the involved nonlinearity are constructed. If there is an intersection, the frequency and amplitude of the limit cycle can easily be determined.

Thus, by definition, the EMR is occured whenever $\omega_p = \omega_\ell$. To avoid the resultant dramatic failure, the next two sections are devoted to study the main two factors affecting both frequencies $\omega_p$ and $\omega_\ell$.

## III. Effect of the Automatic Voltage Regulator AVR on $\omega_p$ and $\omega_\ell$:

In the preceding section, the approach of determining the resonant frequency of the electromechanical oscillation for the large scale power system has been studied.

If the factors affecting this frequency along with the frequency of the limit cycle are studied carefully, the EMR resonance is completely overcome.

In this section, a simple graphical relationships are plotted between the normalized value of the power angle $\delta$ and the frequency $\omega$. Fig. 2-a shows the relationship of the magnitude of $\Delta\delta/\Delta V_f$ against for one-machine with infinite busbar system without its AVR.

The maximum value of the magnitude is occured at resonant frequency $\omega_{p1} = 2.7$ rad/Sec as shown in curve (2.a). However, the resonant frequency for the same power system with its AVR is $\omega_{p2} = 6.4$ rad/Sec, as shown in Fig. 2-b. This explains an important property, that is the presence of the AVR increases the resonant frequency for one-machine with infinite busbar system.

To calculate the frequency of the limit cycle for the one-machine with infinite bus system, one can contruct the Nyquist and $-1/N$ plots as shown in

Fig. 3.

The intersection frequency $\omega_\ell$ and the magnitude of the nonlinearily can be easily calculated as explained in [6]. Fig. 3-a shows the Nyquist plot for the system without AVR with limit cycle frequency $\omega_{\ell 1}$ = 1.9 rad/Sec.

Fig. 3-b for the one-machine with infinite bus system and the machine is connected with its AVR with $\omega_{\ell 2}$ = 1.6 rad/Sec.

Comparing both curves, it is noticed that the presence of the AVR decreases the limit cycle frequency. Therefore, both frequencies $\omega_{\rho 1}$ and $\omega_{\ell 1}$ can be separated using the AVR in order to avoid the EMR problem (AVR is of forced excitation [5]).

Fig. 4-a indicates the relationship between $\Delta\delta/\Delta V_f$ and the frequency $\omega$ as Fig. 2-a, but for three machine subsystem.

It is clear from Fig. 4-a and Fig. 4-b that the maximum magnitudes for the 3-machine system with and without AVR are occuring at 9.1 rad/Sec and 11.6 rad/Sec respectively. Then, it is concluded that the presense of the AVR increases the resonant frequency but with smaller rate.

The Nyquist plot for three machine system without AVR is shown in Fig. 5-a with limit cycle frequency $\omega_{\ell 1}$ = 6.8 rad/Sec.

However, if the AVR is connected to each machine of the three machine system the limit cycle frequency is decreased to 5.4 rad/Sec as shown in Fig. 5-b.

In the end of this section, one can conclude that the effect of connecting AVR's to each machine is effective in avoiding the EMR problem.

However, for the large scale systems the AVR's of the dominant machines are more effective than the ones in the other machine.

Note that the magnitude is decreasing as the frequency increases in all previous systems.

IV. Effect of the Mechanical Inertia on $\omega_\rho$ and $\omega_\ell$:

It is important to notice that the mechanical inertia is very effective in the resonant frequency. A three and four-machine systems are used in this section in order to study this effect.

Fig. 6-b is plotted for four-machine system with resonant frequency of 7.9 rad/Sec and amplitude

~~0.135. The three-machine magnitude of ($\Delta\delta/\Delta V_f$)~~ against $\omega$ is shown in Fig. 6-a. The resonant frequency and maximum magnitude in the later figure are 9.1 rad/Sec and 0.23 respectively.

The interpretation of that is the resonant frequency is increasing as the mechanical inertia decreasing.

Similarly, Fig. 7-a and 7-b indicate that the limit cycle frequency is increasing as the mechanical inertia decreasing but with very small rate.

Therefore, in order to separate the resoneant frequency and the limit cycle one, the mechanical inertia must be decreased. This can be done by separating the large scale system into subsystems to the extent that the EMR problem is completely excluded.

## CONCLUSIONS:

The paper presents a practical approach to calculate the resonant frequency of the electromechanical oscillation in large-scale electric power systems. The electromechanical resonance problem has been carefully studied.

The most important two factors affecting the resonance frequency have been investigated.

First, the presense of AVR is so important in avoiding EMR problem since the AVR helps in separating the resonant frequency from the limit cycle one. Thus the resonance problem can be avoided. Second, the Mechanical inertia is an important factor that has been shown that the large-scale system can be subdivided in order to avoid the EMR problem.

There are another factors affecting the resonant and limit cycle frequencies such as the time constant, the electric load and automatic speed regulators. These are subjects the authors are investigating.

Finally, the trade-off between all of the mentioned factors under known power system condition in order to avoid the resonance occurance completely is also subject of future work.

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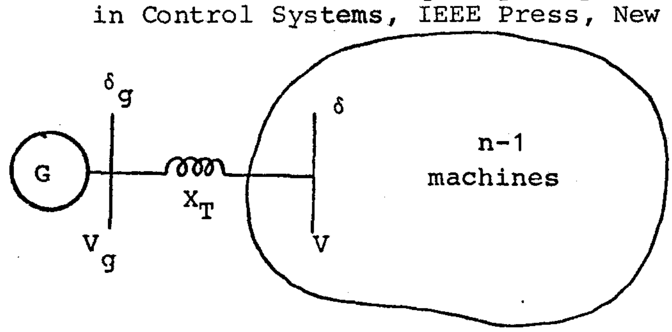


Fig. (1): n-machine inter-connected power system under study.

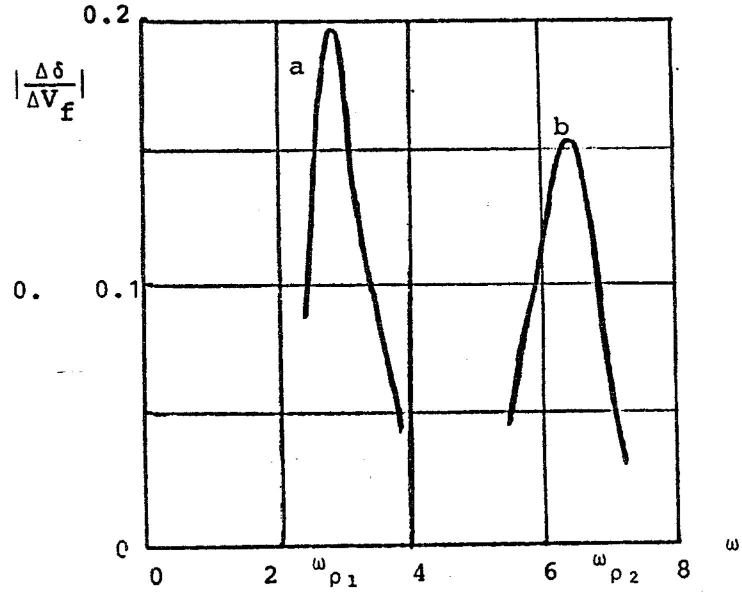


Fig. (2): A normlaized power angle response of one machine with infinite bus,
a) without AVR. b) with AVR.

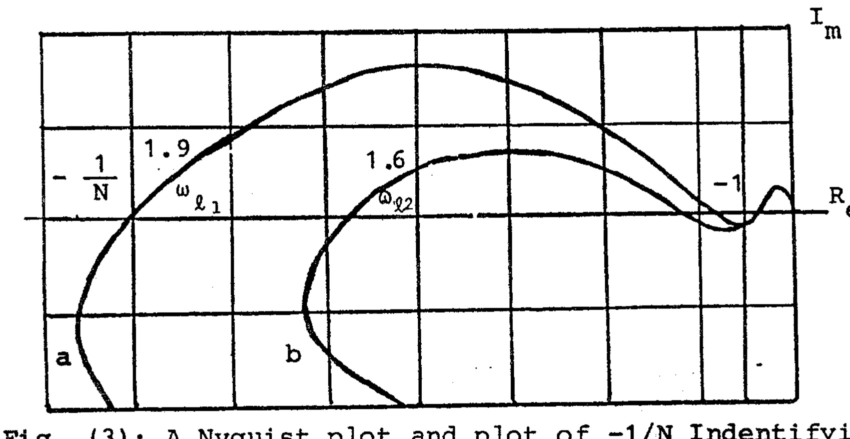


Fig. (3): A Nyquist plot and plot of -1/N Indentifying limit cycles for the system of Figure 2.
a) without AVR. b) with AVR.

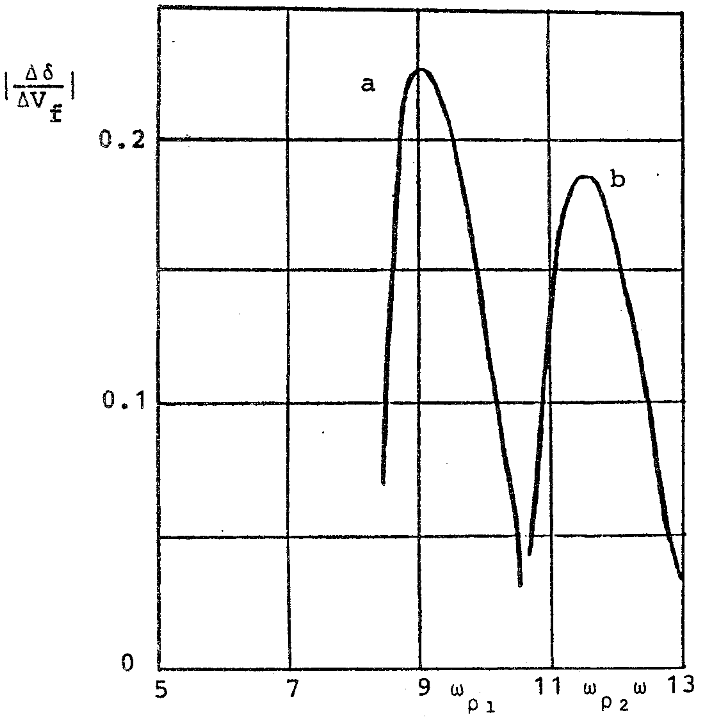


Fig. (4): A normalized power angle response for 3-machine subsystem,
a) without AVR , b) with AVR.

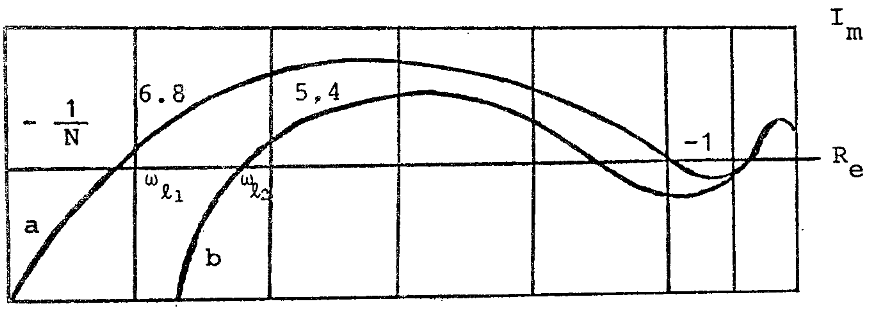


Fig. (5): A Nyquist plot and plot of -1/N indentifying the limit cycles for the system of Fig. 4.,
a) without AVR , b) with AVR.

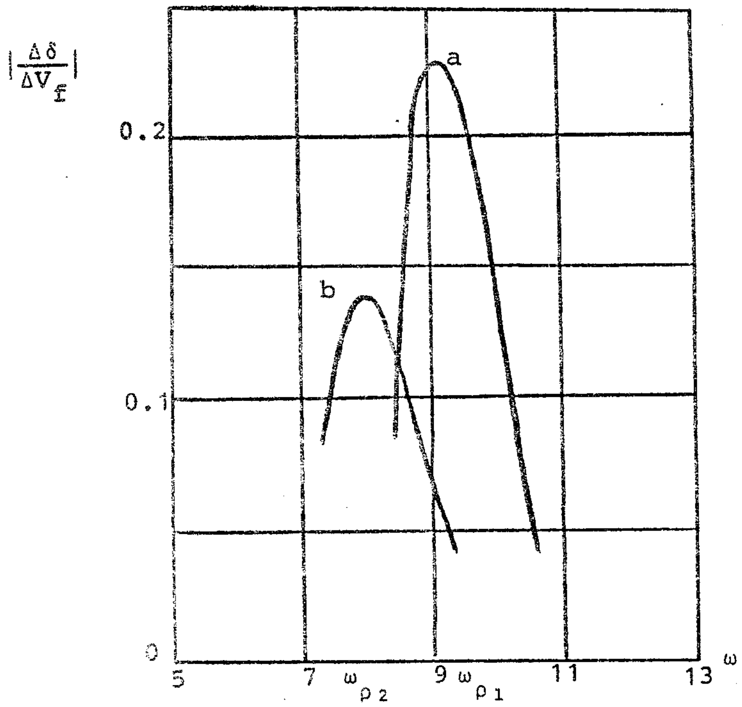


Fig. (6): A normalized power angle response of power system,
a) 3-machine , b) 4-machine.

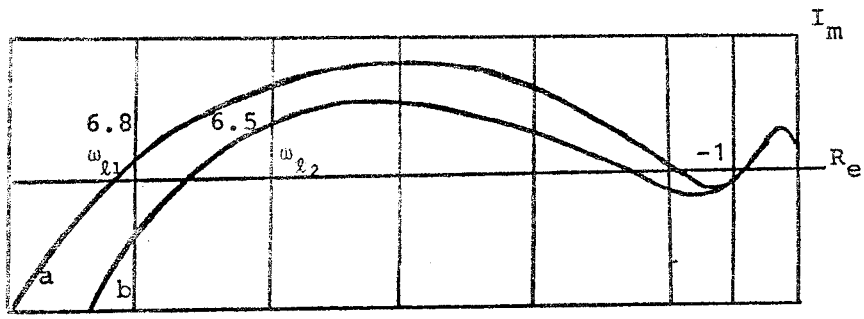


Fig. (7): A Nyquist plot and plot of -1/N identifying the limit cycles for the system of Fig. 6.,
a) 3-machine , b) 4-machine.