Enhancing Efficiency of Modal Exciting Regulators Operating in Complex Power System

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***Abstract*—Efficient tuning of multiple exciting regulators operating in a complex power system, their interference, correction of setting to achieve best oscillation damping are the issues considered in the article.**

Keywords- power system; exciting regulator; synchronous machine

I. Introduction

Aligning with the requirements of energy performance efficiency the development of the modern power grids follows integration and utilization of new generation technologies, control and monitoring systems. It should be noted that the Azerbaijan power system has had a 30% growth in installed capacity since the year of 2000. In the Azerbaijan power system there are 52% of steam-turbine plants (STP), 14% combined-cycle plants (CCP), 2% gas turbine power plants (GTPP), 15% hydro turbine plants (HTP), 17% diesel plants (DP). Alongside with those types of power plants the near-term development of the power system is associated with accelerated introduction of small water power stations (SWPP) and wind power stations.

The synchronous machines of these plants are known for their different dynamic parameters which stipulate disparity in the behavior under transient conditions. Their exciting regulators primarily designed for voltage regulation and damping of electromechanical oscillations do differ from those currently in operation not only by the structure but also by regulation settings.

Thus, automatic voltage regulators power system / stabilizers (AVR+PSS) are becoming more commonly used along with automatic exciting regulators of the strong action (AER-SA) and automatic exciting regulators of proportional action (AER-PA) which were widely utilized in the post-Soviet area.

Under their integration the tuning of AVR+PSS is done with reference to field trials using the infinite capacity nodes – this enables quite rough-and-ready modeling of a complex power system impact.

Thus, one can raise a question on capability of diverse regulators in a complex power system to effectively act upon damping properties of the power systems under high and low disturbances, as well as, interference of new and earlier installed exciting regulators – this necessitates correction of settings based on best oscillation damping.

II. Subject of Inquiry

Effectiveness of two AER-SA dominating in the Azerbaijan power system and AVR+PSS of UNTROL-500 type was the subject of research and analysis.

AER-SA are five-channel controllers regulating excitation as a function of voltage deviation and its derivative, frequency deviation and its derivative, excitation current deviation derivative [1]. AVR+PSS of UNITROL-5000 type are four-channel controllers regulating excitation as a function of voltage, frequency, active and reactive powers [2, 3].

Every channel in the AER-SA has its own gain coefficient, whereas, AVR+PSS does perform gain function as a sum of all deviations on every channels (K_A). Stabilization channels (P and f) are also amplified following summation of their signals through gain coefficients Ks.

These factors stipulate diversity in the control factors to achieve maximum of the electromechanical oscillation damping.

To ensure efficiency of diverse exciting regulators utilized in the power system the authors applied progressive approximation method in the power system diagram with reference to the modal theory: complex amplitude method. A sub-transient mathematic model was used, i.e. taking account of transients in the damping loops of synchronous machines. The calculations were completed using “NEPLAN” software package.

III. Example Primitive System

At first the authors have reviewed a simple scheme: synchronous machine – infinite capacity node where the synchronous machine was represented by parameters of a single-shaft unit PGU-400MW linked to infinite capacity node via a 100km of 220kV overhead transmission line.

<u>The objective at this stage is</u>: adjustment of AVR+PSS channel settings (gain channel K_A and stabilization channel K_S), recommended by the field trials; definition of adequate settings for AER-SA and AVR+PSS. Maximal damping of transient period was selected as performance criteria (Table I).

TABLE I. SETTINGS RECOMMENDED BY THE FIELD TRIALS

K_A	Ks	α , 1/s	ω , 1/s
75	**0**	–0.446	4.555
	1	–0.544	4.437
	3	**–0.654**	**4.219**
	5	–0.612	4.028
	8	–0.495	3.901
150	**0**	–0.575	4.306
	1	**–0.597**	**4.112**
	3	–0.472	3.918
	5	–0.376	3.861
	8	–0.294	3.834
300	**0**	**–0.477**	**4.011**
	1	–0.387	3.912
	3	–0.281	3.857
	5	–0.228	3.842
	8	–0.186	3.835

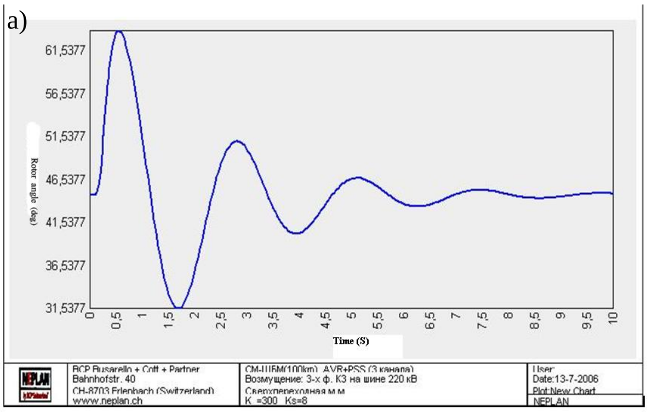
An analysis of results given in Table I shows that the best damping of transient process occurs at the following coefficients of the AVR+PSS (UNITROL-5000) controller: K_A =150, K_S=1. At the same time, the field trial recommendation was: K_A =300, K_S=8.

Comparison of transients curves under high disturbance (3-phase short circuit near synchronous machine node, $t_{disc.}$ = 0.15s) confirms that controller setting of K_A =150 and K_S=1 provides better transient (Fig. 1).

Similar oscillation rates (α = –0.599; ω = 4.241) are demonstrated by ARV-SA integrated into excitation system of the same synchronous machine with the following settings: Kou=50, K'u=1, Kf=5, K'f=3. The nature of the electromechanical transient is similar under the same disturbance (Fig. 2).

This calculation demonstrates that AER-SA with the following settings Kou=50, K'u=1, Kf=5, K'f=3 and AVR+PSS set up K_A =150, K_S=1 are similar as far as electromechanical transient is concerned, at least, for the simple system.

Given example points out at differences in the control coefficients of the subject automatic exciting regulators providing identical maximum possible oscillations damping rate.



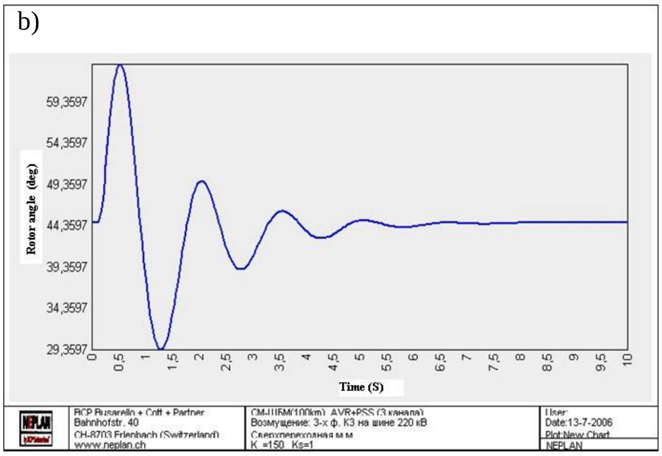


Figure 1. Transient in the Synchronous Machine – Infinite Capability Node scheme AER – UNITROL-5000: a) K_A=300, Ks=8; b) K_A=150, Ks=1

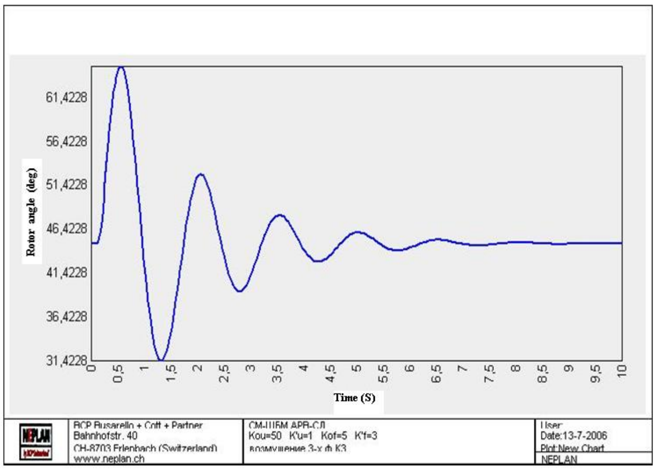


Figure 2. Transient in the Synchronous Machine – Infinite Capability node scheme, AER-SA: K_{ou}=50, K'u=1, Kof =5, K'f=3

IV. EXAMPLE COMPLEX SYSTEM

At the next stage the authors have reviewed real complex power system containing 14 equivalent generators, 110 – 220 – 330 – 500kV power grid, 199 tie-stations including 103 loads.

The calculation method comprises a number of consecutive steps:

1. Eigenvalues in the given complex scheme are defined provided that there are no controllers installed. Under these conditions the eigenvalues describe "natural" damping in the power system stipulated by, mainly, dynamical properties of synchronous machines.

Table II lists such eigenvalues and synchronous machines greatly contributing to formation of oscillations at fundamental frequencies provided that there are no automatic exciting regulators installed.

TABLE II. EINGENVALUES FOR THE COMPLEX SCHEME

α, 1/s	ω, 1/s	f, Hz	Synchronous machines (SM) largely contributing to low-frequency components of oscillations
–0.140	5.057	0.805	SM Shimal
–0.218	5.490	0.874	SM Shirvan G1
–0.257	6.487	1.032	SM Shamkir G2
–0.310	5.911	0.941	SM-Sumgayit IES 1G
–0.348	7.039	1.120	SM- MinGES G5,6
–0.375	6.104	0.971	SM- Shirvan G3
–0.402	7.267	1.157	SM-Shirvan G7
–0.427	7.731	1.230	SM-MinGES G1,4
–0.462	7.314	1.164	SM-Baki G1
–0.468	7.399	1.178	SM-MinGES 2G
–0.470	7.591	1.208	SM- Shirvan G5-6
–0.510	6.611	1.052	SM-Sumg IES
–0.546	6.911	1.100	SM-Sumgayit IES G2
–0.603	8.212	1.307	SM-AzTES 500 kV
–0.608	8.464	1.347	SM- AzTES 330 kV

The analysis demonstrates that fundamental frequencies of oscillations are within f=0.8÷1.35Hz, i.e. electromechanical shock-excited oscillations are of low-frequency nature. The lowest frequency and attenuation – (–0.14 ± j5.058). With reference to recommendation as provided in [4] such the value is indicative of weak oscillation damping ($|\alpha| < 0.3$). The following two components as noted in Table II can also be considered as weakly damped – those are stipulated by rotor oscillations at synchronous generators of Shirvan thermal power station and Shamkir hydropower station.

The oscillation process of the synchronous machine of a PGU-400 single-shaft unit of Shimal thermal power station (Tj=13.5 sec.) largely contributes to the dominating shape of the free electromechanical oscillation (–0.14 ± j5.058). All synchronous machines in the power system do contribute variously (distribution coefficient of amplitude of oscillation) to the oscillation shape.

Fig. 3 demonstrates phasors indicating degree of participation of every synchronous machine in the oscillation process at dominating shape defining stability of the power system.

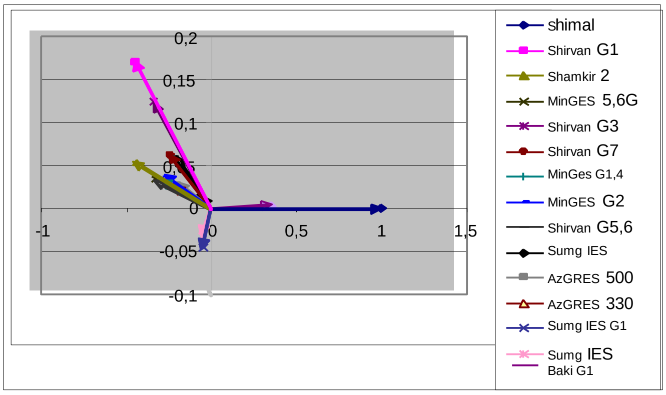


Figure 3. Phasor diagram of distribution coefficients of amplitude of oscillation

TABLE III. THE RESULTS OF THE CALCULATION METHOD

Power Station	Independent introduction of Automatic Excitation Regulator (AER)		AER switched on at all Synchronous machines
	ε	Control factor	ε
1	2	3	4
Shimal	1.692	K_A=140	1.357
Shirvan G1	2.138	Kou=50,Kof=11	1.83
Shamkir G2	1.016	Kou=5, Kof=11	1.15
MinGES G5,6	1	Kou=5, Kof=11	1.46
Shirvan G3	1.648	Kou=50,Kof=11	1.832
Shirvan G7	1.13	Kou=50	1.381
MinGES G1,4	0.993	Kou=5	1.023
Baki G1	2.08	K_A=250	1.762
MinGES G2	1.008	Kou=50,Kof=11	1.06
Shirvan G5-6	1.412	Kou=50	1.43
Sumgait IES	1.22	K_A=300	1.366
Sumgayit IES G2	1.21	K_A=300	1.37
AzGRES 330 kV	1.17	Kou=50,Kof=11	1.52
AzGRES 500 kV	1.35	Kou=50,Kof=11	1.29

2. Independent introduction of automatic exciting regulators is carried out at synchronous machines of the stations which identify different oscillation components and, at the same time, the settings of the controllers are adjusted to achieve maximal possible damping at their own fundamental frequencies.

The results of the calculation method are provided in column 2 of Table III.

The Table III lists sensitivity indexes demonstrating effect of tuned control coefficients of AER of a given synchronous machine on "natural" damping coefficient at fundamental frequency ($\varepsilon = \alpha_{Max} / \alpha_{ccr}$). It also lists control coefficients assisting with maximal possible damping of a oscillation component. The analysis of this stage demonstrates the following:

a) Dominating weak decaying component resulted from oscillation at synchronous machine at PGU-400 Shimal TPS is inside a zone of weak damping [4]. Supported by settings of AER of G-1 at Shirvan TES it is possible to take the oscillation component away from the zone of weak damping.

b) Overall raise in damping factors is achieved at the cost of control coefficients against voltage deviation Kou and K_A.

Thereby, recommended value for K_A at AVR+PSS of UNTROL-5000 type are higher than those at AER-SA, however, they are lower than recommended values based on field trials of new units. Identical conclusion was drawn when defining adequate settings of UNITROL-5000 and AER-SA in the scheme of synchronous machine – infinite capacity node.

c) introduction of excitation control coefficients on derivatives of frequency K'_f and excitation current K'_{if} at AER-SA on real power at UNITROL-5000 does not result in increase of maximal damping coefficients, and in some case does reduce it.

d) Confirmed that settings of AER engaged at one of synchronous machines do not affect "natural" damping of other synchronous machines.

3. By engaging Automatic Excitation Controllers (AER) at all synchronous machines of the power system at next stage we can observe change in components of fundamental oscillations (column 4, Table III) – that has an irregular character. So, looking at ε values one can say that damping coefficients of the components (sensitivity coefficients) caused by oscillations at synchronous machines at Shimal thermal power-station, G-1 of Shirvan TES, G-1 of Baku cogeneration plant are reducing, in other case we note increase in damping coefficients of oscillation components. This is stipulated by interference of AER settings of various synchronous machines in the power system. At the same time introduction of all AERs and selection of AER settings aimed to maximize damping coefficients of individual components does not resolve the main issue: dominating components of oscillation remains to be weak decaying /0.14x1.357=0.19<0.3/ and caused by contribution made by synchronous machine at Shimal thermal power-station.

Two other closest components of the oscillation are considered as satisfactory damped ones.

Fig. 4 shows a transient in a complex system at disturbance caused by disconnection of 200kV overhead transmission line at the 2nd Mingechaur station having automatic reclosure set at t=0.25 sec. The curve demonstrates change in rotor angles between synchronous machines of PGU-400MW unit at Shimal thermal power station and AzTES 330kV.

4. A series of calculations were performed to identify damping coefficient dynamics (α) of dominating component of oscillation and possibility of keeping it at stress regimes, up to the regime defined by safety factor on condition of aperiodic static stability (Ks =20%).

The regimes of the power system were defined by total load flow at the 220 – 330 – 500kV main Mingechaur to Apsheron overhead transmission line. To gain matched results the stress transients across all power regimes were introduced by the same method. Variations were performed with K_A coefficient of AVR+PSS UNITROL-5000 installed at synchronous machine of Shimal thermal power-station (PGU-400) that has most contribution to the dominating component.

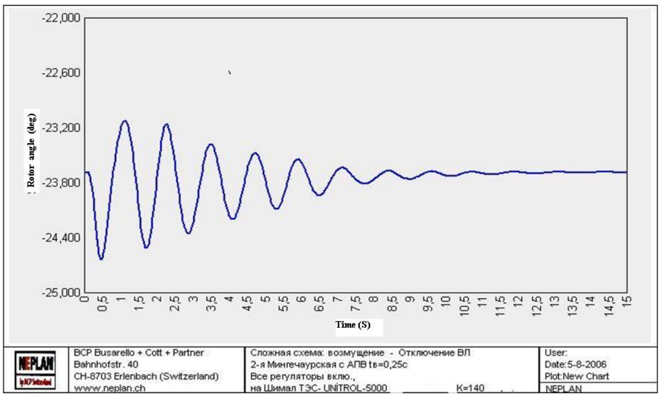


Figure 4. Transient in the complex system

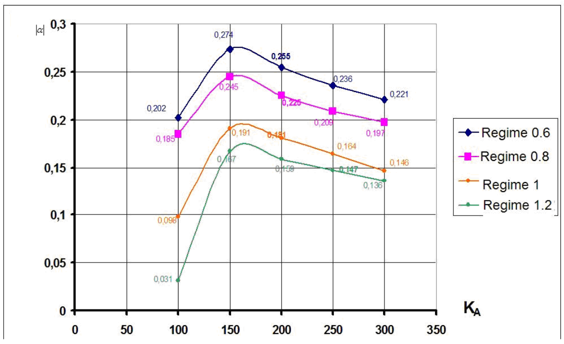


Figure 5. Dependence of damping coefficient on amplification coefficient of AVR+PSS UNITROL-5000 at Shimal TPS at various regimes of power system

As one can note, neither options provides satisfactory damping of dominating component of free electromechanical oscillation. K_A = 150 is the best value achieved.

CONCLUSIONS

Methodical approach based on modal theory enables compatibility of Automatic Excitation Regulators of various types operating in complex system, in particular, AER-SA and AER-PSS. Attaining best damping of the electromechanical oscillations is selected as the evaluation criteria.

The methodology of staged study comprises:

- studying a simple scheme (defining adequate settings for AER-SA and AVR+PSS securing damping as identical as possible);
- studying a complex scheme (evaluation of "natural" damping, determination of sensitivity factors for the damping rates under a single and widespread engagement of AER at all synchronous machines, assessment of interference);

The calculations were performed for a complex Azerbaijan power system known for its centralized (concentrated generation) nature – such the configuration explains weak reaction on damping properties of controller loops against frequency of excitation regulators of both types.

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