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PSS Design for the Hellenic System with Partial Interconnection to Turkey

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***Abstract*— This paper describes the effects on the interarea modes of the Hellenic Power System of its radial connection with an isolated generating area in the European part of Turkey. It is shown that significant mode shape changes occur and poorly damped power oscillations may appear between Greece and Turkey involving also the interconnection of Greece to the North. Two possible system operation cases are studied: case A with all lines in operation (strong connection), and case B for a weak interconnection due to a critical line outage in the North East of Greece. Analysis shows that a near strong resonance occurs in the latter case. A Power System Stabilizer (PSS) is designed for a Hellenic generation plant mainly involved in the poorly damped oscillation modes and is able to restore adequate damping in all cases.**

***Index Terms*—Inter-area oscillations, modal interaction, near strong resonance, Power System Stabilizer**

I. Introduction

The creation of an interconnected pan-European network and the increasing demand for secure power exchanges among the UCTE members has brought up the problem of lightly damped power oscillations. In the past, UCTE recordings have shown that low frequency oscillations (~0.2Hz) appear by time to time in the European network [1]. The cause of these oscillations has not been clarified.

The future interconnection of the UCTE network with Turkey may further decrease this frequency causing additional small signal stability problems [2]. As a first measure, UCTE proposed the evaluation of existing PSS parameters and the retuning of these devices in order to increase generator damping torque at low frequencies. The methodology based on Single Machine – Infinite Bus (SMIB) approximation that is often used to tune a PSS may not be effective since the small signal stability studies should be based on proper dynamic models for the major part of the interconnection. The problem is complicated by the numerous factors that influence power oscillations (load dynamics, controller settings and modal interaction).

Power exchanges between different systems, or islanded parts thereof, also excite low frequency oscillations involving many generators. Furthermore network changes may affect the frequency and damping of these modes and can pose a challenge to power system operation.

This paper deals with an interesting problem that can arise during temporary parallel operation of the UCTE network with electrical islands of neighbouring systems, due to bilateral market contracts. Such a case is the temporary interconnection between Greece and Turkey that was established for the summer of 2008 to face summer peak loads in Greece. Poorly damped power oscillations may appear in this case, while the shape of dominant intra-area modes is affected. Moreover, a change in system topology close to the interconnection lines may change significantly the frequency of the Greece-Turkey mode and bring it close to that of the interarea mode between Greece and its Northern UCTE neighbouring systems. This modal interaction may lead close to a near strong resonance, creating thus possible risks for secure power system operation.

To overcome the above problems, a Power System Stabilizer (PSS) is designed in the paper for the units of a Hellenic generating plant mainly involved in the poorly damped oscillation modes. The designed PSS is able to restore adequate damping to all lightly damped modes in the case of normal operation, as well as in the case following a contingency in the North East of Greece that severely weakens the interconnection to the part of Turkey.

II. Temporary Greece – Turkey Interconnection

In the summer of 2008 a new 400 kV interconnection line was commissioned between the N. Santa (GR) and Babaeski (TR) 400kV substations. The total length of the line is 127 km. A temporary radial connection between Greece and a generation island of Turkish East Thrace was foreseen, to accommodate a limited volume of power exchanges (up to ~ 250 MW) from Turkey to Greece and some exports from Greece to the said part in Turkey [3].

The connection of the isolated part of the Turkish system to Greece originates at Filippi 400/150kV substation and ends up in Turkey (Fig. 1). Filippi substation is connected to the 150 kV part of the system via 2 autotransformers of nominal capacity 280 MVA each, while the 400 kV bus of the substation is connected to the area of Thessaloniki by a single circuit 400 kV line. In N. Santa a 400/150kV substation is to be constructed, but for the time period of the temporary connection the substation will operate as a 400 kV switching centre. Power exchanges should be achieved with the parallel operation of the Hellenic interconnected system and the Turkish electrical island that comprises 4 combined cycle generation

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units and some electrical loads. A similar operation had been performed during 2007, when a Turkish electrical island was connected to the Hellenic Power System at the 150 kV level and realized exchanges up to 160 MW.

In case of an opening of the 400 kV line between Filippi and Thessaloniki, the power import from Turkey will be transmitted through the 150 kV network weakening the interconnection. This causes the appearance of lightly damped power oscillations, as will be shown in this paper.

The 400kV parallel operation was planned to last from June 2008 up to the end of 2009, or up to the permanent connection of the Turkish System to UCTE, in case that this occurred earlier.

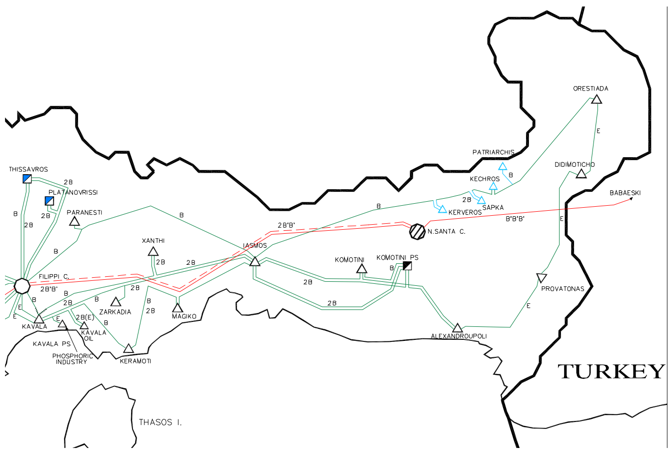

Fig. 1. 400 kV line between Greece and Turkey

III. STUDY DESCRIPTION

The small signal analysis study performed in this paper is based on a computer model of the South Eastern European system (former UCTE Zone II). In this model, the entire EHV (400 kV and 220 kV) network of the Balkan states has been included, as well as the 150 kV network in Greece. The remaining UCTE system (Central and Western Europe) is modelled by a properly tuned Thevenin equivalent, so as to match the interarea UCTE frequency of 0.2 Hz mentioned in the Introduction. All units in SE Europe are described in detail including generators, excitation systems and governor – prime movers. This model has been used in previous studies [4,5] for the analysis of power exchanges within countries and system dynamics.

For the study of temporary interconnection with Turkey, the high voltage Hellenic system was updated, so as to depict the 2008 topology. This comprised increased load level, new or upgraded transmission lines and 400/150 kV substations. Dynamic and network data of the Turkish generating island were provided by the TEIAS, the Turkish TSO. The electrical island comprised 4 combined cycle generators and was connected to the rest of the system through the N. Santa – Babaeski transmission line.

In the first part of this paper no power system stabilisers are modelled in the Hellenic and the Turkish system, while in Section V a PSS is designed and introduced in the model. Studies were performed using Siemens-PTI PSS/E program, as well as CEPEL's PACDYN software.

IV. MODAL ANALYSIS

A. *Case A: Strong interconnection (no line outage)*

In this case the 400 kV line Filippi – Thessaloniki, as well as all other lines are considered in operation. The dominant electromechanical mode eigenvalues with damping ratio below 5%, as well as the interarea modes involving the Hellenic system are shown in Table I. Their characterization is based on the elements of the right eigenvectors referring to generator rotor angles. The names of these modes are given in accordance with the geographical location of the involved generators in the Hellenic system.

TABLE I
STRONG INTERCONNECTION DOMINANT MODES (PACDYN)

No	eigenvalues (s^{-1})	ζ %	Hz	Mode
1	-0.623 +j 12.52	4.97	1.99	Local 1 (KARDIA)
2	-0.592 +j 12.21	4.85	1.94	Local 2 (AG.DIMITR)
3	-0.338 +j 7.21	4.68	1.15	Local 3 (KASTRAKI)
4	-0.218 +j 5.95	3.67	0.95	Intra-area Thrace
5	-0.227 +j 5.84	3.89	0.93	Intra-area Central GR
6	-0.117 +j 5.17	2.26	0.82	Intra-area GR – TR
7	-0.496 +j 3.89	12.6	0.62	Interarea GR
8	-0.544 +j 1.480	34.5	0.24	Interarea UCTE

The Hellenic units participate in three intra-area modes of low damping ($\zeta < 5\%$) and two interarea modes. It is notable that the interarea modes are well damped. A more detailed analysis on the Hellenic modes is given in [5,6].

In the intra-area Thrace mode (0.95 Hz), the plants located in the North East region of Greece (Komotini and Thisavros) oscillate against the units of the Turkish system [6]. In the intra-area Central GR mode (0.93 Hz), the two extremities of the Hellenic system, i.e. the groups of generators of the southern part of the country (Megalopolis, Ladon and Kastraki) and the Thrace units in the North East, oscillate in phase against the units that form the center of the system. In the intra-area GR- TR mode, the North East Hellenic units together with the three Hamidabad and Alarko Turkish power plants oscillate in phase against the rest of the Hellenic system. Note that the GR-TR mode is lightly damped with a damping ratio close to 2% and is the dominant mode for the system considered.

Concerning the interarea oscillations, in the GR mode (0.62 Hz) all the Hellenic generators, together with the Turkish plants, oscillate in phase against the rest of the Interconnection, while in the UCTE mode all the modelled units of SE Europe oscillate in phase against the North and West of the UCTE (modelled as an infinite bus).

The shapes of the GR-TR intra-area and the interarea GR modes are given in Fig. 2, as calculated by PACDYN.

The small signal analysis is verified through the simulation of a three-phase 120ms self-cleared short circuit in the middle of the Thessaloniki - Filippi line. The simulation was run in PSS/E. The responses of active power flows in the Greece-Turkey and Greece-Bulgaria interconnecting lines are given in Fig. 3. It is interesting to note that in the GR-BG interconnection, shortly after the fault clearance the oscillation frequency is close to 0.6Hz (interarea GR mode), but after a few seconds the dominating frequency is about 0.8Hz, i.e. close to the frequency of the lightly damped GR – TR mode.

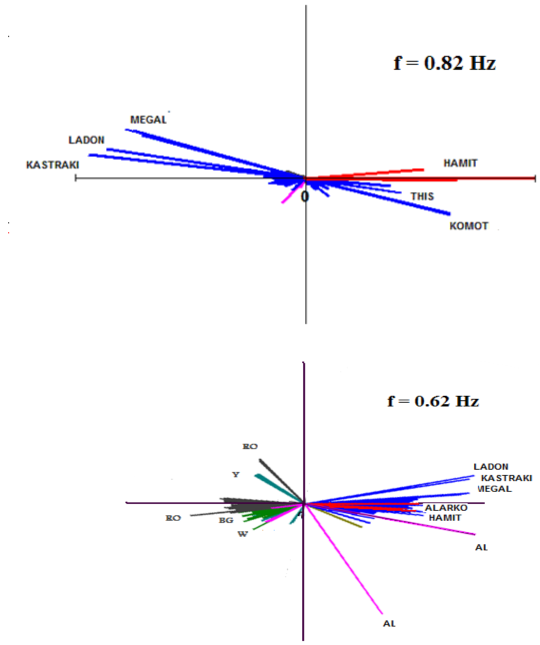

Fig. 2: Mode shape of the GR -TR (0.82 Hz) and the interarea GR (0.62 Hz) modes (no line outage).

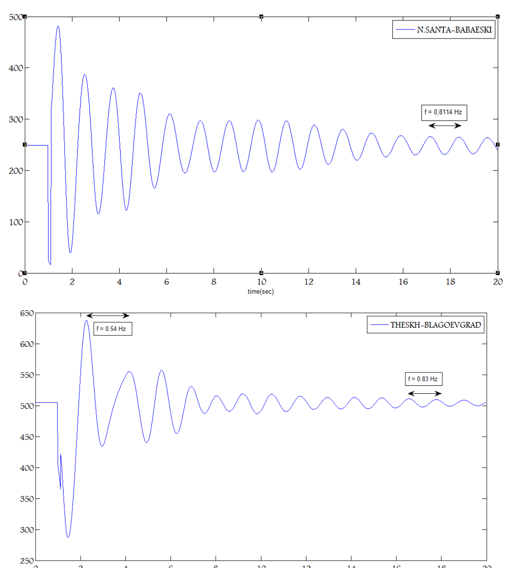

Fig. 3: Simulation of the power flow through the GR – TR and GR - BG interconnection line (no line outage).

B. *Case B: Weak interconnection (line outage)*

In this case the 400 kV Filippi-Thessaloniki line is considered open (e.g. after a fault). The dominant electromechanical mode eigenvalues with damping ratio below 5%, as well as the interarea modes of the Hellenic system are shown in Table II.

Due to the opening of the 400 kV connection path, two eigenvalue pairs come close to each other in frequency (modes GR-TR and interarea GR) and they interact strongly concerning their damping. More specifically, the interarea GR mode is now the one most poorly damped, while the GR-TR mode that was the dominant oscillation before, has now a satisfactory damping ratio.

TABLE II
WEAK INTERCONNECTION DOMINANT MODES (PACDYN)

No	eigenvalues s^{-1}	ζ %	Hz	Mode
1	-0.622 +j 12.52	4.96	1.99	Local 1 (KARDIA)
2	-0.591 +j 12.21	4.84	1.94	Local 2 (AG.DIMITR)
4	-0.338 +j 7.21	4.68	1.15	Local 4 (KASTRAKI)
5	-0.334 +j 6.98	4.83	1.11	Local 5 (TR)
6	-0.174 +j 5.96	2.91	0.95	Intra-area Thrace
7	-0.304 +j 5.67	5.36	0.90	Intra-area Central GR
8	-0.312 +j 4.08	7.62	0.65	Intra-area GR – TR
9	-0.098 +j 3.60	2.73	0.58	Interarea GR
10	-0.538 +j 1.48	34.2	0.24	Interarea UCTE

In order to better understand this modal interaction, the locus of these two eigenvalue pairs is drawn assuming that the 400 kV interconnection line impedance changes gradually from normal value (line on) to infinity (line off). This locus, calculated with the PACDYN software, is drawn in Fig. 4 (only the upper half plane is shown). As the line impedance increases, the interarea GR mode moves to the right while the GR-TR mode decreases in frequency and moves to the left. After a point of minimum distance, the two eigenvalues turn approximately at right angles indicating that they pass near a strong resonance [7,8].

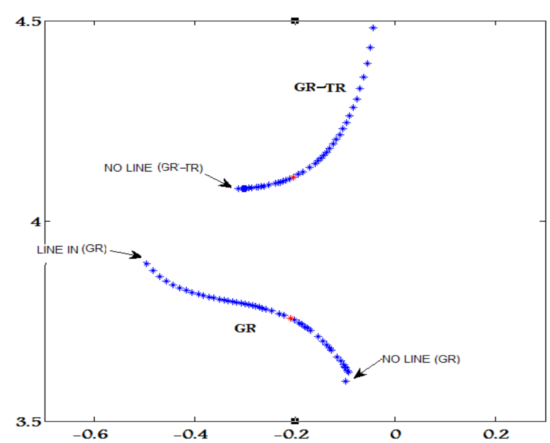

Fig. 4: Eigenvalue loci for gradual increase of line impedance to infinity.

In Fig. 5, a plot of the right eigenvector elements of these modes shows that the shapes of the two modes have come together with the bulk of the Hellenic system units oscillating close to 90^o out of phase to the group of Hellenic Thrace and Turkish units, which oscillate in phase in both modes. This similarity of mode shapes is also an indication of near strong resonance.

A 3-phase short circuit cleared after 120msec by opening the 400kV Thessaloniki - Filippi line was simulated in PSS/E and the interconnecting active power flows are shown in Fig. 6. As can be seen, the dominant oscillation mode for both Greek interconnections is close to 0.6Hz, i.e. the frequency of the interarea GR mode that dominates.

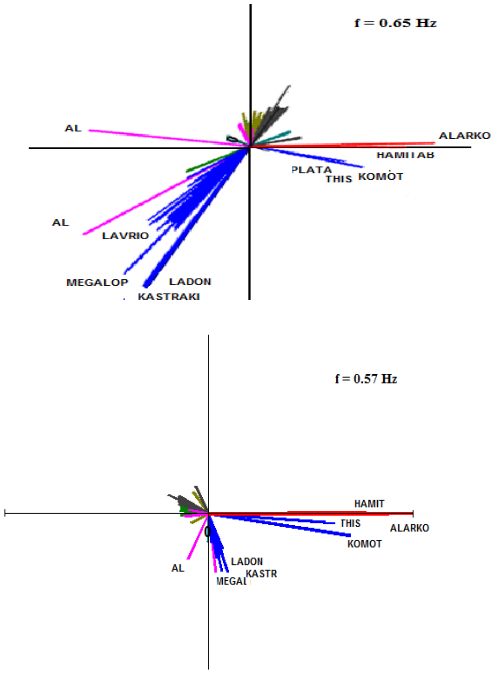

Fig. 5: Mode shape of the GR – TR (0.65 Hz) and the inter-area GR (0.58 Hz) at the point of their minimum distance.

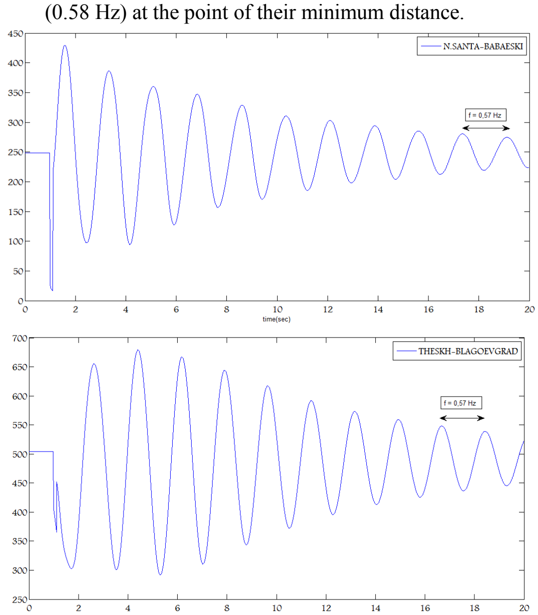

Fig. 6: Simulation of the power flow through the GR-TR and GR-BG interconnection lines (weak connection).

V. PSS DESIGN

Power System Stabilizers have been proven a cost-effective, robust and reliable solution to damp out power oscillations. In the modern interconnected power systems, proper PSS tuning for low frequency oscillations is a difficult task since these modes often evolve hundreds of generators. Modal interaction, such as the one presented in the previous Section, may be a major problem [9, 10, 11]. Moreover, PSS settings should be evaluated considering possible system contingences that modify system dominant modes.

In the studied system, the PSS design has to take into account the near strong resonance that appears after the N-1 contingency considered. The PSS should cope with two dominant poorly damped low frequency modes: the GR-TR 0.82 Hz mode (strong connection) and the interarea GR mode of 0.62 Hz (weak connection due to line outage).

A. Choice of PSS Location

In order to specify the plant where a PSS should be activated to damp out the lightly damped modes, a sensitivity analysis was carried out. This analysis comprised both participation factor analysis, as well as residue computation for a transfer function with input the reference voltage of generator AVR and output the rotor speed. The results of this analysis are summarized in Table V. According to the participation factor index (eigenvalue sensitivity to diagonal state matrix element corresponding to speed), the PSS should be installed at Megalopolis power station, while the residue amplitude favours the Komotini power plant.

TABLE III
PARTICIPATION FACTORS AND RESIDUES FOR DOMINANT MODE

STRONG CONNECTION (GR-TR 0.82Hz)				
Generator	**Participation Factors**	**Residues**		**PSS Compens. Angle**
		Amplitude	**Phase**	
Komotini_3	0.465	**0.276**	77.2	102.8
Komotini_1	0.438	**0.260**	77.3	102. 7
Komotini_2	0.435	**0.260**	77.4	102.6
Megalopol_4	**0.697**	0.140	-4. 2	-175.8
Megalopol_3	**0.630**	0.1272	-6.7	-173.3
WEAK CONNECTION (Interarea GR 0.58Hz)				
Komotini_3	0.516	0.419	111.9	68.1
Komotini_1	0.488	0.393	111.6	68.4
Komotini_2	0.487	0.392	111.6	68.4
Thisavros_1	0.216	0.252	122.3	57.7
Thisavros_2	0.216	0.252	122.3	57.7
Thisavros_3	0.216	0.252	122.3	57.7

As mentioned above, participation factors are dimensionless sensitivity indices of eigenvalues to the state matrix diagonal elements. Residues are sensitivity indices of the eigenvalue shift when a scalar feedback is activated between TF input and output. Also, they are an index of mode observability and controllability from the TF input and output respectively. With respect to participation factors, residue amplitude also considers AVR gains and it provides the exact compensation angle to damp out at a specific mode. For a positive feedback loop, the needed compensation angle is the supplementary angle of residue phase [8]. It has to be mentioned that these two indices are sensitive in cases of strong resonance since they tend to take very large values at an exact strong resonance [7, 8].

In this study, the PSS will be designed in Komotini power plant, not only because the residue approach is considered as a more accurate, but also because this plant participates in all critical modes (i.e. Thrace, GR-TR, Central GR and interarea GR), as well as in both studied cases, i.e. full and weak system interconnection.

Moreover, the compensation angle that PSS should provide is positive, i.e. it can be achieved with a positive feedback PSS and its absolute value is smaller than the one that Megalopolis PSS would needed. The PSS will use generator shaft speed as input. Since the Komotini is a combined cycle plant, PSSs are considered in the two gas turbines to be on the safe side. A PSS can be added to the steam unit as well, but this may not be in operation at partial loads.

B. PSS design through GEP transfer function

The evaluation of the GEP(s) transfer function (Generation Excitation and Power system) is a robust technique for PSS design since this transfer function changes only slightly over different operating points [12]. The GEP has input the AVR reference voltage and machine torque as an output. The GEP is computed considering the power-angle loop open by setting generator inertia at a very high value. For a positive PSS feedback loop the desired compensation angle is the opposite of GEP phase at the oscillation frequency.

The GEP for the Komotini units was calculated both by a SMIB equivalent and with the full system (and large inertias) using PSS/E. In the former case the plant was connected to an infinite bus through an equivalent line, whose impedance corresponded to short circuit level at the connection bus. In the latter case, the system is represented either with all lines in service (Case A), or for the weak connection (Case B).

Table IV shows the compensation angle that the GEP approach proposed for a PSS in Komotini for the critical modes for cases A and B. As seen, the single machine approach gives quite good results in both cases, while the difference in required compensation between the two cases is quite small.

TABLE IV
KOMOTINI GEP COMPENSATION ANGLE FOR GR-TR AND INTERAREA GR MODE

Mode	Frequency	SMIB	Full System
GR – TR	ω = 5.17 r/s	102.4°	Case A 103.2°
Inter-area GR	ω =3.6 r/s	88.0°	Case B 89.2°

Comparing to the required compensation as shown by the residues of Table III it is seen that the GEP approximation gives good results in Case A, but has a relatively large error in case B (92° instead of 68°), due to the strong modal interaction.

C. PSS design through the residue evaluation

The PSS is designed with two equal compensation blocks, a washout filter and a gain. Each block is a first order phase lead-lag that adds half of the desired compensation phase and is maximized at the frequency of the critical mode. The exact design method may be found in [13,14]. The PSS is designed for the required phase corresponding to the dominant mode of the strong interconnection case (5.17 r/s), which is the normal operating condition. The PSS is subsequently tested for both the normal and the weakened system conditions.

The proposed PSS transfer function is given by:

$$H_{PSS}(s) = \frac{5s}{1+5s} K_{PSS} \frac{1+0.5642\,s}{1+0.06586\,s}\,\frac{1+0.5642\,s}{1+0.06586\,s} \quad (1)$$

The desired PSS gain is evaluated by gradually increasing K_{PSS}. After some value, the eigenvalues of the critical mode change direction and the gain increase has to stop [11,15].

In Fig. 7 the root locus plot of the dominant modes as the PSS gain in Komotini increases from 0 to 10 pu, is given for cases A and B. In Case A, the GR-TR mode shifts to the left up to a gain of 5. The same applies to the Thrace mode. On the other hand the Central GR mode shifts very slightly to the right, due to the strong participation of the Komotini plant.

In case B, the dominant interarea GR mode is shifted to the left, but the GR-TR mode starts moving to the right for gains above 5 pu. The Thrace and the local mode of the Turkish plants are sifted far to the left almost without frequency change.

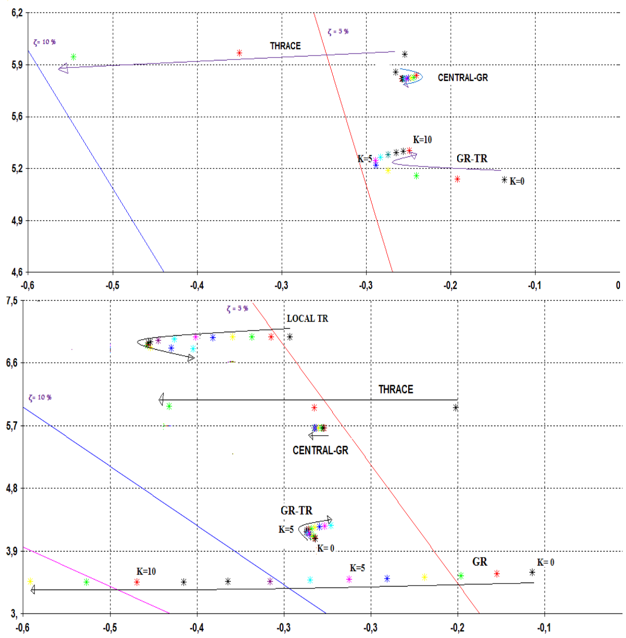

Fig. 7: Root locus of the GR-TR, S-GR and Thrace mode as the PSS gain increases (strong and weak connection)

From the above root locus plot, the optimal PSS gain is estimated as 5 pu. In Table V the eigenvalues of the dominant modes with the PSS activated are given.

TABLE V
DOMINANT MODES WITH PSS

Line in			Line out			Mode
Eigenvalue	ζ %	Hz	Eigenvalue	ζ%	Hz	
-1,884 +j 5,50	32,4	0,88	-1,15 +j 6,25	18,1	0,99	Thrace
-0,217 +j 5,80	3,7	0,92	-0,312 +j 5,67	5,5	0,90	C. GR
-0,248 +j 5,29	4,7	0,84	-0,318 +j 4,15	7,76	0,66	GR-TR
-0,546 +j 3,89	13,9	0,62	-0,279 +j 3,50	7,9	0,56	GR
-0,548 +j 1,47	34,9	0,23	-0,540 +j 1,47	34,6	0,23	UCTE

In both cases (strong and weak interconnection) the PSS shifts to the left the GR-TR, interarea GR and the Thrace mode but the intra-area Central GR mode is almost unaffected. In practice the damping of this mode is increased by the PSSs installed to units located in the South of the Hellenic System, but these stabilizers are not considered in this study.

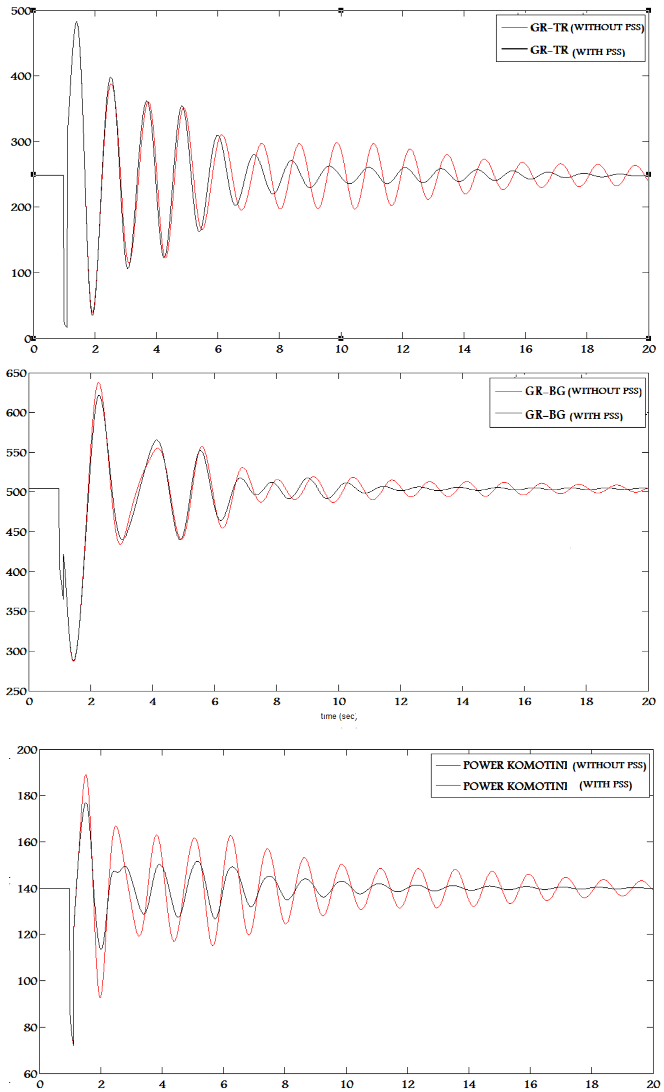

Fig. 8: Simulation of active power flow of GR-TR, GR-BG interconnections and Komotini generation with and without PSS (strong connection).

In Figs. 8 and 9 the active power flow of interconnection lines, and the Komotini active generation response after a simulated 3-phase short circuit at the middle of the 400kV Thessaloniki - Filippi line are shown. In the first figure, the short circuit is self-cleared after 120msec (case A), while in the second one, the short circuit is cleared after 120msec by line opening (case B).

VI. Conclusion

Though much attention has been paid to “global” European modes of very low frequencies (~0.2 Hz), power oscillations of a little higher frequency (0.5 – 0.8 Hz) can also risk system stability and integrity, as shown in this paper.

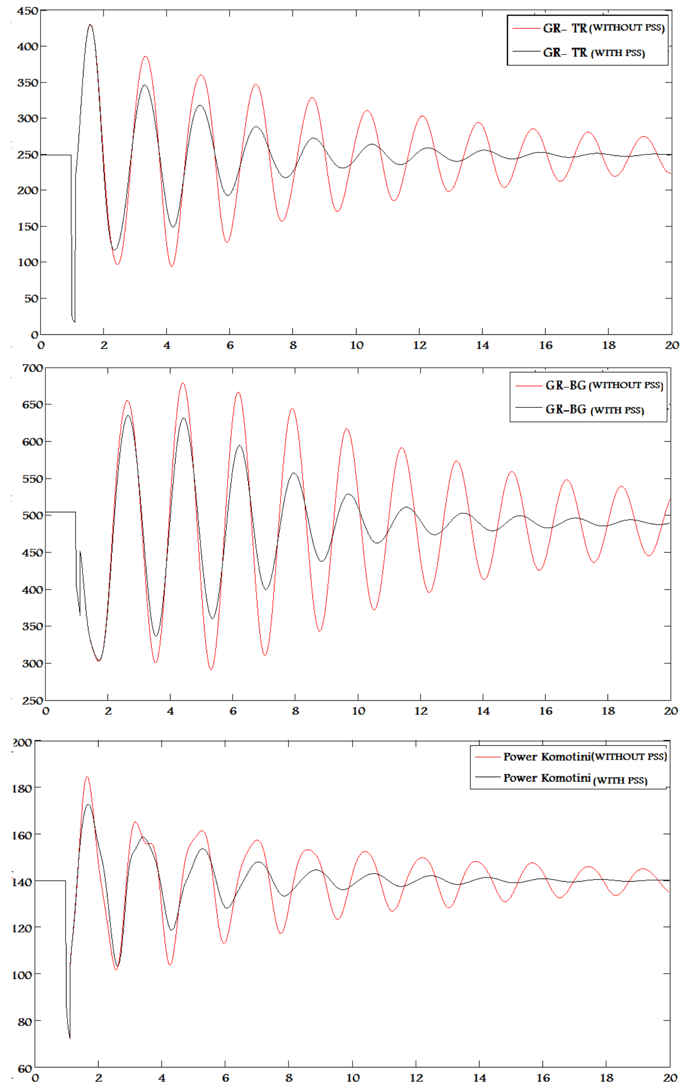

Fig. 9 Simulation of active power flow of GR-TR, GR-BG interconnections and Komotini generation with and without PSS (weak connection).

The parallel operation of the Hellenic system with a generation island of Turkey introduces a new lightly damped intra-area mode. This mode interacts strongly with existing intra- and interarea modes involving the Greek system. In case of a critical line loss in the North Eastern part of the Hellenic Interconnected System the operating point comes close to a strong resonance between this mode and the interarea mode of the Hellenic System. This phenomenon may be a substantial threat, since the damping of the interarea mode reduces drastically.

A Power System Stabilizer was designed in the paper that was able to provide acceptable damping to the interacting modes for both cases of strong (normal operation), or weakened (line loss) interconnection. Other, relatively poorly damped modes in the system were not controlled by other PSSs, as the focus of the paper was on the Greece-Turkey Interconnection.

Of course, proper full system studies and coordinated PSS setting evaluation is needed to provide a more effective solution of low frequency power oscillations before implementing the proposed stabilization. The aim of this paper was however to show that a possible near resonance problem exists and that it is solvable by standard PSS design, even in a single power plant.

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