MAXIMISATION OF R.E.S. PENETRATION IN GREEK INSULAR ISOLATED POWER SYSTEMS WITH THE INTRODUCTION OF PUMPED STORAGE SYSTEMS

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ABSTRACT

In the present paper, the maximisation of the Renewable Energy Sources (R.E.S.) penetration in non-interconnected Greek insular systems with the introduction of pumped storage systems is investigated. The proposed power systems are introduced in the examined islands with the following goals:

- the maximisation of the available renewable energy sources exploitation
- the minimisation of the electricity production cost
- the improvement of the security of the electrical systems.

The achievement of the abovementioned targets is investigated through the case studies implementation in characteristic isolated insular power systems of small (Kasos – Karpathos, Astypalaia), medium (Rhodes, Lesvos) and large size (Crete). In the examined cases, the fundamental power source is the wind power. The pumped storage systems aim at the wind power stochastic production adaptation to the power demand. The possible available potential of any other renewable energy sources (biomass, geothermy) in the examined insular system, may contribute to further limitation of the conventional thermal generators power production.

The proposed systems are dimensioned and the corresponding investments are evaluated. Finally, the dynamic security of the existing and the proposed electrical systems is evaluated with the simulation of the corresponding systems operation.

The conclusions of the present paper are:

- The R.E.S. penetration percentage in the Greek insular systems may exceed 80% of the annual energy demand.
- The electricity production cost is minimized, even in the isolated systems of small size.
- The corresponding investments exhibit very good economical indexes, regardless the possible availability of initial capitals subsidy. In case of initial capitals subsidy availability, the investments exhibit quite attractive economical indexes.
- The dynamic security of the proposed systems is improved considerably, due to the existence of hydro turbines in the power production systems. The necessity for spinning reserve from the thermal generators is restricted.

1. INTRODUCTION

1.1. Wind power penetration in Greek non-interconnected systems

The majority of the Greek islands constitute non-interconnected power systems. All the consumed energy is produced by autonomous thermal power plants, installed on their respective landmasses. The excellent wind potential observed in these insular territories has triggered the installation of considerable wind power, mainly on those of medium and large size (Crete, Rhodes, Lesvos). However, most Greek islands constitute weak electrical systems of small size with several power quality and dynamic security problems. These facts limit the wind power penetration considerably [1-3].

Despite the improved wind generators behaviour concerning the produced power quality and the utility network compatibility, the wind stochastic nature does not allow the achievement of high wind power penetration [4-9]. Moreover, wind energy rejection in isolated power production systems is significant because:

- The power demand exhibits intensive seasonal variations. In the cases of the Greek islands, these are imposed mainly by the touristic sector, due to which the power demand increases considerably during summer. The total installed wind power in a Greek isolated power system during a year is not permitted to be over the 30% of the maximum annual power demand of the previous year. In an isolated power system with intensive seasonal power demand variations, the power demand during low power demand seasons will be significantly lower than the maximum power demand. Hence, the installed wind parks will be underemployed during the low power demand seasons, exhibiting high wind energy rejection.
- The requirement for power production system dynamic security and stability impose an upper threshold to the thermal production substitution from the wind power. The stability of an isolated power production system is affected negatively for increasing ratios of wind power penetration over the total power demand (especially when it exceeds an upper limit). In these cases, a sudden power production loss, probably caused by an abrupt wind velocity gust or a turbine blade damage, may result to a partial or total black-out, if the system is not sufficient to undertake in a short time period the power production loss. Therefore in order to ensure the stability of the system, a wind power penetration upper limit relative to the power demand is set.

These constraints may lead to considerable wind power rejection in isolated power systems. The wind power rejection depends on the total installed wind power in the isolated power system and the power demand scale.

Despite the above constraints, the Greek islands represent highly attractive territories for wind parks installations. This is due to:

- the excellent wind potential
- the increased power demand, observed mainly in the isolated power systems of medium and large scale
- the increasing energy production specific cost by the conventional thermal power plants, caused mainly by the highly increasing fossil fuels prices worldwide.

1.2. The introduction of wind powered pumped storage systems in Greek non-interconnected islands

The wind powered pumped storage systems introduction, and especially the wind – diesel – PSS introduction, in isolated power production systems with high wind potential, has been widely studied for both the Greek territory [10-18] and internationally [19, 20]. These systems, in general lines, aim at:

1. the exploitation of the local, renewable and environmentally friendly wind energy
2. the minimisation of the, generally, imported fossil fuels consumption
3. the minimisation of the energy production cost, enforcing the local economy.

In the present paper, the ultimate scope of the introduced wind powered pumped storage systems is to adapt the stochastic wind power production to the power demand of the insular non-interconnected system. The operation of the proposed wind powered pumped storage systems is revealed in figure 1.

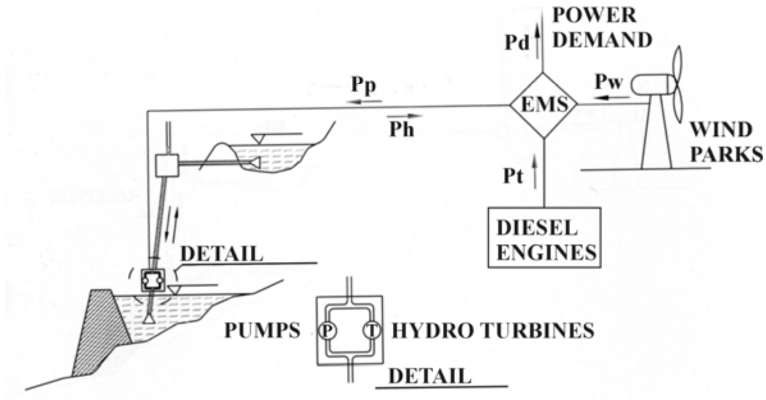

Figure 1: Wind parks, pumped storage and thermal plants power production system.

In figure 1, the system is provided with power P_w by the wind parks, at a certain time point. The Energy Management System (EMS) checks if the instant wind parks produced power P_w is higher than the instant power demand P_d. The following cases are distinguished:

1. If $P_w>P_d$, the power demand is covered totally by the wind parks. The PSS pumps are provided with the wind power surplus $P_p=P_w-P_d$, in order to be stored in the PSS upper reservoir. In case the PSS upper reservoir is full, this power surplus cannot be stored. This power exploitation in other applications (hydrogen production, desalination, etc) is not investigated in this paper.

2. If $P_w<P_d$, the produced wind power is totally offered to the power demand. At the same time, a power supplement $P_h=P_d-P_w$, produced by the PSS hydro turbines, undertakes the wind power shortage. In case the PSS upper reservoir is empty, this power shortage cannot be undertaken by the hydro turbines. The thermal power plants are employed to supply the required power $P_{th}=P_d-P_w-P_h$.

A special case may be distinguished for isolated systems of small size. In this case of, generally speaking, weak systems, it will not be safe to base all the power production on wind parks, even if $P_w>P_d$. An upper limit on the wind power penetration is introduced. Due to the existence of hydro turbines, this limit may be much higher than the corresponding upper wind penetration limit introduced in isolated thermal power plants. Similar limitations are introduced also when $P_w<P_d$.

Specifically, in case of small size non-interconnected systems, the abovementioned cases may be reformed are follows:

1. If $P_w>P_d$, the wind powered offered directly to the power demand is limited to $P_{wd}=a\cdot P_d$. In the present study a is set equal to 50%. The thermal power plants provide the requested power to cover the power demand, $P_{th}=P_d-P_{wd}$. The PSS pumps are provided with the wind power surplus $P_p=P_w-P_{wd}$, in order to be stored in the PSS upper reservoir.

2. If $P_w<P_d$, the maximum wind power offered to the power demand is set equal to $P_{wd}=a\cdot P_d$ (a=50% in the present study). The hydro turbines provide power equal to $P_h=P_d-P_{wd}$. In case the PSS upper reservoir is empty, thermal power plants are employed to provide the required power $P_{th}=P_d-P_{wd}-P_h$.

With the proposed power production system, the thermal power plants are used only in case that no wind parks and hydro turbines power production may be provided. This is the fundamental difference between the proposed system and a conventional one, based on thermal power production.

1.3. The contribution of other Renewable Energy Sources in Greek insular systems

Solar potential

The solar potential met in Greek islands is also remarkable. However, the introduction of large scale photovoltaic parks in Greek isolated power systems seems to be non-competitive, due to several parameters of technical and economic nature. The most important of them are:

- The low power density of photovoltaic panels. For an installed peak power of 100 kWp, an area of approximately 3.000 m^2 is required.

- The low efficiency of photovoltaic panels. For the solar potential met in Greek islands, the annual total mean efficiency of a photovoltaic park is configured around 15-17%, while in summertime, the maximum efficiency will not exceed 23%. For comparison reasons, it is mentioned that the capacity factor of a wind park installed in a Greek island and operating under the wind potential usually met in Greek insular territories, is approximately 40%.
- The high initial specific cost of photovoltaic parks, configured at 5.000 – 6.000 €/kWp, while the initial specific cost of a wind park installed in Greece is approximately 1.000 €/kW.

For the above reasons, photovoltaic panels cannot be considered as a promising technology towards the maximisation of R.E.S. penetration in isolated systems and the minimisation of the electricity production cost. Their use is restricted in applications of small size. In the present study, the introduction of photovoltaic systems is not investigated.

Biomass

Biomass may constitute a considerable source of power in some islands with biomass sources. The main biomass sources met in Greek islands may arise from:

- olive oil production residues (cuttings and kernels)
- municipal wastes.

Considerable biomass potential in Greek islands is met mainly in Crete and Lesvos, where extended olive oil production and municipal waste exist. Moreover, municipal wastes of capable quantities may be met in Rhodes, mainly due to the highly developed touristic sector.

In the abovementioned islands, biomass stations may provide a basis power production.

Geothermy

Remarkable geothermal potential is met mainly in two non-interconnected systems of small and medium size, namely in the islands of Milos and Lesvos respectively. In Lesvos, a geothermal power plant of 8 MW nominal power is already under construction. In Milos, several geothermal research bores have demonstrated the existence of high geothermal potential.

Geothermal power plants may provide a basis power production in both islands.

2. THE INVESTIGATED ISOLATED SYSTEMS

The proposed wind powered pumped storage systems are introduced in several isolated Greek insular systems of small, medium and large size. Specifically, the proposed systems are examined for the following non-interconnected islands:

- Kasos – Karpathos (small size)
- Astypalaia (small size)
- Lesvos (medium size)
- Rhodes (medium size)
- Crete (large size).

In the examined cases, the fundamental power source is the wind power. The pumped storage systems aim at the wind power stochastic production adaptation to the power demand, as described thoroughly in the introductory section. Only in the case of Lesvos, the only island that combines considerable geothermal and biomass potentials, the introduction of a biomass and a geothermal station is introduced as basis power plants.

The whole study of each system consists of the following steps:

- Dimensioning of the systems, according to the operation philosophy described previously.
- Economic evaluation of the corresponding investments, based on specific initial and operation & maintenance costs models.
- Dynamic security evaluation of the proposed electrical systems, for the islands of Crete and Rhodes.

The results of the above tasks are presented below.

3. DIMENSIONING OF THE SYSTEMS

3.1. Calculation Data

The main power demand features for the investigated islands are presented in table 1.

	Crete	Rhodes	Lesvos	Astypalaia	Kasos - Karpathos
Annual energy demand (MWh)	2.812.658,75	742.156,00	345.136,56	5.418,68	6.083,22
Annual maximum power demand (MW)	560,27	185,39	67,00	1,78	2,00
Reference year	2005	2005	2006	2004	2006

Table 1: Power demand features of the examined islands.

The values of table 2, concerning the proposed power production systems features, were introduced. The head height, the reservoirs capacities and the penstock length were selected in accordance with real site features .

	Crete	Rhodes	Lesvos	Astypalaia	Kasos - Karpathos
Head height (m)	800,00	500,00	500,00	400,00	500,00
Penstock length (m)	4.000,00	3.000,00	4.000,00	2.500,00	3.000,00
PSS upper reservoir capacity ($10^6 \cdot m^3$)	12,00	7,00	1,50	40.000,00	300.000,00
PSS lower reservoir capacity ($10^6 \cdot m^3$)	15,00	10,00	2,50	sea	sea

Table 2: Proposed pumped storage systems features.

3.2. Calculation Results

The main features of the characteristic components of the proposed systems were calculated according to the operation philosophy of the proposed systems, presented previously. The calculations were accomplished with a relevant software tool, developed in Wind Energy Lab. In table 3, the power production system components required installed powers are presented, as well as the penstock selected diameters.

	Crete	Rhodes	Lesvos	Astypalaia	Kasos - Karpathos
Wind parks minimum required power (MW)	730,00	230,00	120,00	1,70	2,55
Hydro turbines minimum required power (MW)	450,00	160,00	70,00	0,40	2,00
Pumps minimum required power (MW)	560,00	190,00	100,00	1,25	2,50
Thermal power plants minimum required total power (MW)	470,00	160,00	55,00	1,30	2,00
Penstock diameter (m)	5,80	4,80	3,00	0,60	0,50
Geothermal power plant (MW)	0,00	0,00	8,00	0,00	0,00
Biomass power plant (MW)	0,00	0,00	5,00	0,00	0,00

Table 3: Power production system components required installed powers & penstock diameters.

In figures 2 the R.E.S. penetration is presented for each one of the investigated islands.

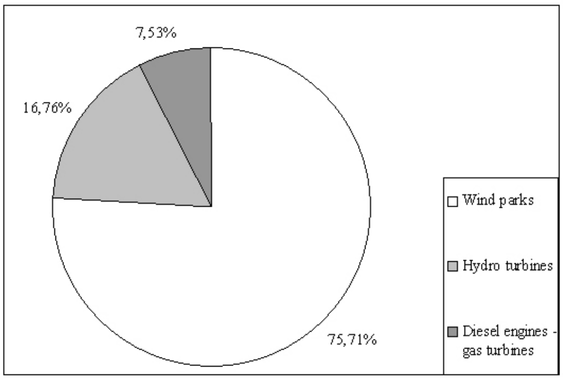

Figure 2a: Energy production percentage contribution in Crete.

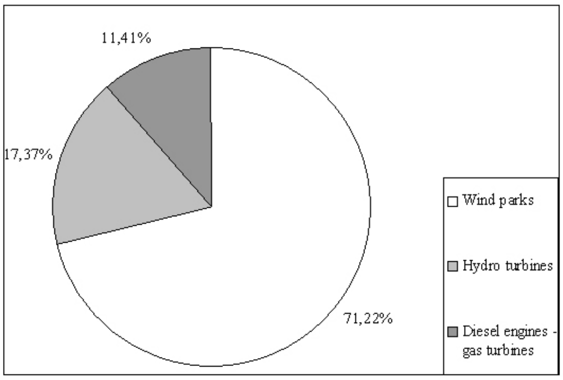

Figure 2b: Energy production percentage contribution in Rhodes.

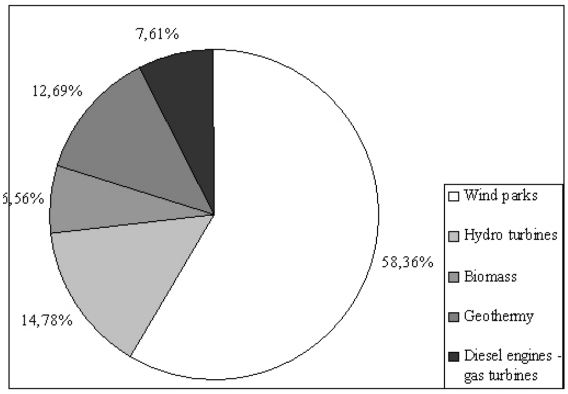

Figure 2c: Energy production percentage contribution in Lesvos.

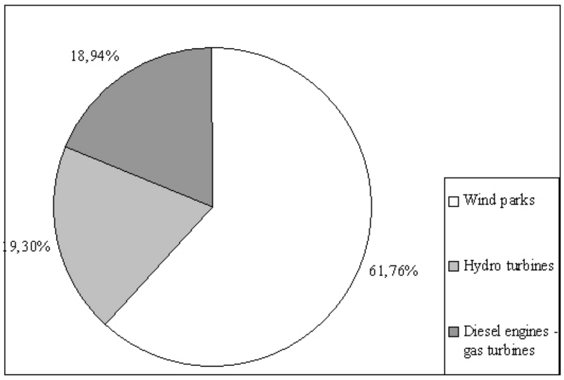

Figure 2d: Energy production percentage contribution in Astypalaia.

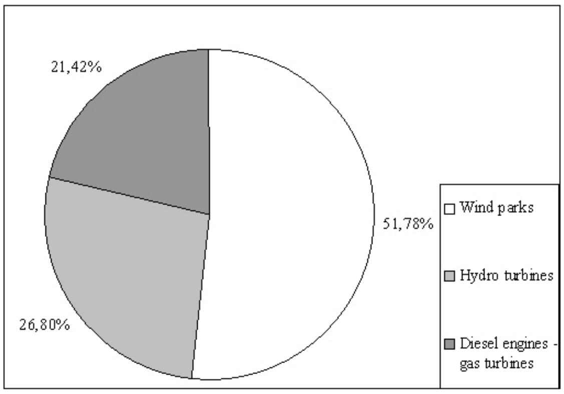

Figure 2e: Energy production percentage contribution in Kasos - Karpathos.

4. ECONOMIC EVALUATION

The proposed systems were economically evaluated. The investments evaluation was based on specific initial and operation & maintenance costs models [21-29]. In large systems there was not assumed any initial cost subsidy, due to the large scale of the investment and the lack of a relevant financial law in Greece concerning such high investments.

The results of the investments evaluation are presented in table 4.

	Crete	Rhodes	Lesvos	Astypalaia	Kasos - Karpathos
Initial cost (M€)	1.408,43	517,66	321,40	6,62	9,62
Initial cost subsidy (%)	0,00	0,00	30,00	40,00	40,00
Electricity price (€/kWh)	0,085	0,085	0,20	0,25	0,30
Internal rate of return (%)	8,47	3,39	15,96	12,04	13,79
Payback period (years)	10,10	14,79	6,14	8,08	6,67
Specific production cost (€/kWh)	0,0549	0,0662	0,0917	0,1121	0,1813

Table 4: Parameters and results of the economic evaluation of the proposed investments.

In table 4, the electricity price was configured according to the existing electricity production specific cost.

5. DYNAMIC SECURITY ASSESSMENT

The analysis of the dynamic performance of the system depends on the quality of the system model. Thus, system modelling may be a very important component of the DSA system. In order to have an accurate system model, the following classes need to be considered: network, system dynamic models, load models [30-34].

- *Network modelling*
  Network modelling includes the representation of lines, generators, transformers, breakers, loads.
- *System Dynamic Models*
  It includes generator dynamic models representing machine electrical dynamic equations at various levels of detail, governors, excitation systems, overexcitation limiters. The wind turbines have been model as induction machines, without any voltage regulator. This is the worst case for the dynamic security of the system.
- *Load models*
  Load has been modelled in the ZIP standard model (i.e., combination of constant impedance, constant current, and constant power).

The dynamic security of the proposed case study systems of Crete and Rhodes is investigated for different operational scenarios and severe contingencies. These scenarios and the simulated contingencies are illustrated in tables 5 & 6.

	Crete	Rhodes
Total active power production (MW)	258,20	79,00
Total wind power production (MW)	207,00	55,00
Total hydro turbines production (MW)	23,20	10,00
Total thermal power production (MW)	28,00	14,00
Wind power penetration (%)	80,17	69,62
Total nominal power of synchronized hydro turbines (MW)	150,00	75,00
Thermal spinning reserve (MW)	5,00	2,00
Contingency	loss of 80 MW of wind power	loss of 25 MW of wind power

Table 5: Operation scenarios and contingencies for the dynamic security assessment of the proposed power production systems.

As it can be observed from table 5 the simulation of the systems is focused on low load scenarios with high wind power penetration, which is the worst case for the dynamic security of the system. Furthermore, the simulated contingencies are the loss of a wind power production, almost equal to 30% of the total power production.

In table 6 one more contingency under different operation conditions is investigated for each one of the examined islands. According to table 6 data, the operation of the proposed systems without the support of synchronized hydro turbines and with wind power production storage through the PSS pumps is investigated. The wind power penetration remains high in low power demand operation conditions. The thermal spinning reserve is low. The system's reaction after the loss of considerable wind power production is investigated. The pumps loads are rejected, once the assumed contingencies occur.

	Crete	Rhodes
Total active power production (MW)	258,20	79,00
Total wind power production (MW)	190,00	55,00
Total hydro turbines production (MW)	0,00	0,00
Total thermal power production (MW)	68,20	24,00
Wind power penetration (%)	74,68	69,62
Wind power surplus (MW)	40,00	25,00
Total nominal power of synchronized hydro turbines (MW)	0,00	0,00
Thermal spinning reserve (MW)	30,00	4,00
Pumps operation power (MW)	40,00	25,00
Contingency	loss of 40 MW of wind power	loss of 25 MW of wind power

Table 6: Operation scenarios and contingencies for the dynamic security assessment of the proposed power production systems.

Conclusively, with the implemented dynamic simulation, the systems reactions after severe contingencies under low load scenarios with high wind power penetration are investigated.

Figures 3 and 4 illustrate the frequency of the power systems of Crete and Rhodes respectively, for the systems operation conditions described in table 5 (the contingency is supposed to take place at t=10 sec). It is obvious that the case study systems are able to survive the disturbance and maintain a frequency very close to the nominal one (50 Hz). This means that the operation of a synchronized hydro turbine can benefit the dynamic security of the system.

Figures 5 and 6 illustrate the frequency of the power systems of Crete and Rhodes respectively, for the systems operation conditions described in table 6 (the contingency is supposed to take place at t=10 sec). In this occasion, even if the hydro turbine is not synchronized, the systems are able to survive after the contingencies occurrence, with the rejection of the pumps loads. The frequency is maintained again very close to the nominal one (50 Hz).

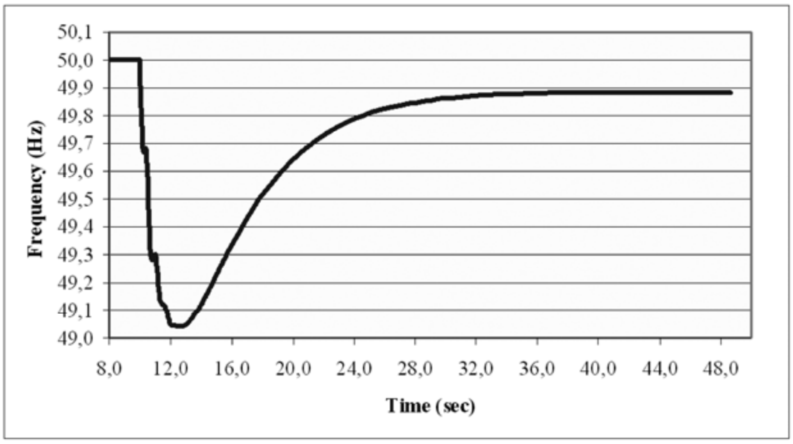

Figure 3: Frequency variation after the contingency in Crete system, with the support of synchronized hydro turbine.

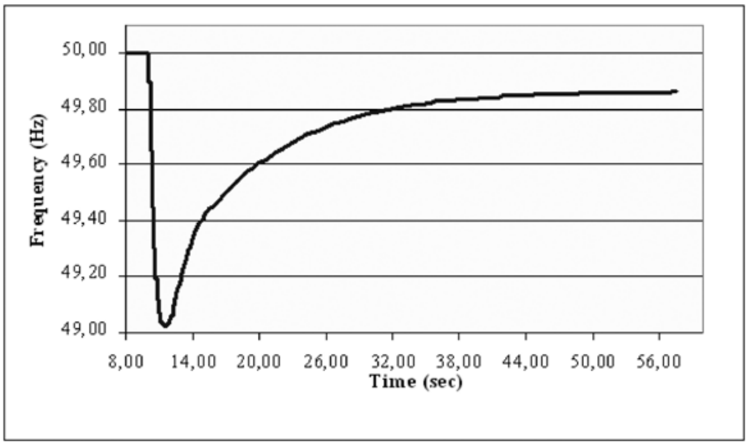

Figure 4: Frequency variation after the contingency in Rhodes system, with the support of synchronized hydro turbine.

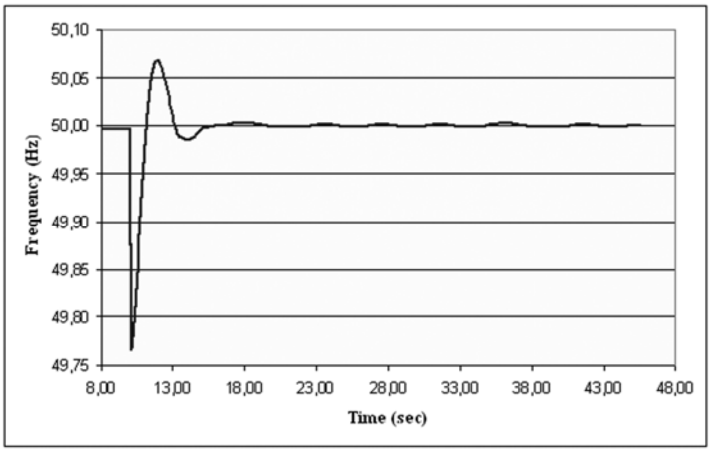

Figure 5: Frequency variation after the contingency in Crete system, with the rejection of pumps loads.

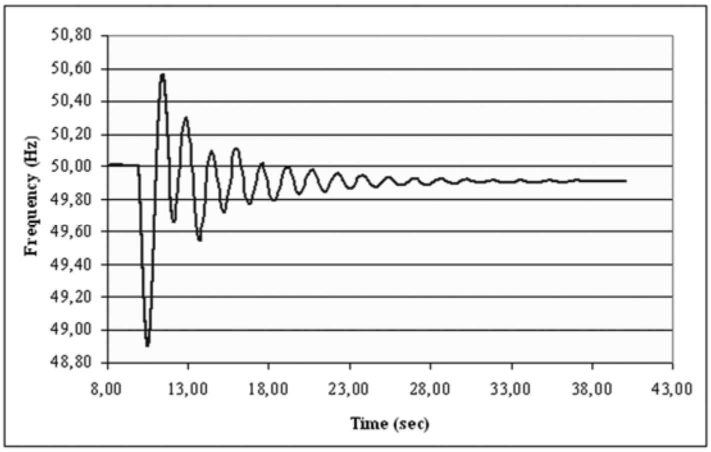

Figure 6: Frequency variation after the contingency in Rhodes system, with the rejection of pumps loads.

7. CONCLUSIONS

The maximisation of R.E.S. penetration in Greek insular isolated power production systems is investigated in the present paper. Five case studies are accomplished.

The proposed systems aim at:

- the islands local energy sources exploitation
- the imported fossil fuels consumption minimisation for the annual electricity production
- the minimisation of the electricity production cost.

The dimensioning, the economic evaluation and the dynamic security assessment of the proposed systems lead to the following conclusions:

- The proposed power production systems may appear attractive economic features under certain prerequisites. These prerequisites are:
  - ✓ the provision of a subsidy on the investments' initial costs
  - ✓ the configuration of the produced energy vending price according to the existing electricity production specific cost.
- In isolated power systems of great size (Crete case) the projects appear better economic indexes due to the larger projects scale. On the other hand, the projects high initial cost and the large scale technical works constitute the projects implementation main problems.
- In medium size isolated systems (Rhodes and Lesvos case), the lower projects initial costs and the lower scale technical works, make the project financially and technically more feasible, although the investments economic indexes are not so attractive.
- The existence of geothermal or biomass potential may help remarkably towards the minimisation of the thermal power plants production.
- The wind energy penetration may reach the 90% of the annual electricity production, with a corresponding thermal power production limitation.
- In isolated power system of small size (Kasos – Karpathos, Astypalaia) the R.E.S. penetration is limited to 80%, due to safety reasons. On the other hand, the existence of the initial cost subsidy and the small scale of the requested technical works, make the project more economically and technically feasible.
- The dynamic security of the proposed systems may be ensured once some of the PSS hydro turbines are synchronized. This may be achieved even if at a certain time the wind power production is higher than the power demand, hence no hydro turbines power is produced. In that case, the hydro turbines may be kept synchronized if necessary (low power demand, intensive weather conditions) by consuming a low percentage of the wind power surplus, instead of storing it in the PSS upper reservoir, or waste it, in case it can't be stored (low pumps power or full upper reservoir). This may lead to an increase of the required installed wind power.

- The environmental benefits from the minimisation of the fossil fuels consumption and the national economies enforcement, not taken into account in the present study, will raise the attractiveness of the proposed power systems.

In the majority of isolated power production systems worldwide, the electric energy production is based on imported fossil fuels. The peculiarities met in those systems result in an expensive and instable power production. The increasing fossil fuel prices recorded during the last years raise the electricity production cost and affect negatively the local economies. Moreover, the sensitive ecosystems frequently met in those systems are considerably influenced by the operation of thermal power plants.

High renewable energy sources potential is frequently recorded in non interconnected islands. The exploitation of this potential may provide the solution for the power production and the viable local communities' development. In many occasions, high renewable energy penetrations, based mainly on hydroelectric power, biomass and wind power, have been achieved in those systems [35].

The highest wind power penetration recorded in an isolated power production system worldwide does exceed 20% [35]. This is due to the wind stochastic nature. The wind stochastic nature is faced with the introduction of pumped storage systems.

The introduction of wind powered pumped storage systems in isolated power production systems, although widely studied, does have so far many applications. The proposed wind powered PSS in this paper, may represent highly promising solutions for an alternative, environmentally friendly electrification of isolated power production systems with high wind potential. The proposed systems proved to be technically feasible and dynamically secure. The corresponding investments may exhibit attractive features and the relevant projects enforce the local economies, giving the ability to be independent from imported fossil fuels. Finally, the exploitation of renewable, environmentally friendly energy sources may provide one more chance for a sustainable, viable worldwide development.

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